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FOREWORD

This is the final report on the study "Control of Mainline Freeway and Freeway-Freeway Connectors for Bottleneck Alleviation." The study examined the feasibility of metering freeway connectors and mainline sections to improve traffic flow at bottlenecks downstream of the metering locations. A set of guidelines is presented which will enable operating agencies to determine the appropriateness of such control.

The principal finding in the study was that connector metering should be used only when ramp metering is either not feasible or is insufficient to maintain uncongested flow through a bottleneck location.

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16. Abstract

The objective of this study was to explore the application of mainline and freeway-to-freeway connector metering for freeway bottleneck alleviation. The study involved a review of the literature; visits to sites with existing, planned or candidate implementations, modeling and analysis of metering systems including various options with respect to inclusion of ramp, connector and mainline metering for five representative sites; development of guidelines for operations personnel; and generation of simulation scenarios for future, detailed studies.

Successful connector metering implementations are documented. This technique was generally shown to be a very useful adjunct to ramp metering when high volume connectors contribute substantially to operational bottlenecks. Successful implementations of mainline metering have been limited almost solely to bridge and tunnel control. Freeway mainline metering has not been implemented (except for one manual metering implementation) and should be considered only for extreme circumstances as a means to manage freeway congestion not addressable by other means.

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TABLE OF CONTENTS

Section		Page
1.0	INTRODUCTION	1
2.0	GUIDELINES PERTAINING TO THE IMPLEMENTATION OF CONNECTOR AND MAINLINE METERING	3
	2.1 Traffic Control Treatments	3
	2.1.1 Metering of Access to Tunnels and Bridges	3
	2.1.2 Freeway-to-Freeway Connector Metering	6
	2.1.3 Metering of Mainline Traffic	11
	2.2 Assessment of Applicability of Connector and Mainline Metering	11
	2.2.1 Assessment Factors	12
	2.2.2 Screening Guidelines	12
	2.2.3 Factors Affecting the Success of Re-Design/Control for Freeway-to-Freeway Interchange Related Bottlenecks	14
	2.2.4 Example Applications of Screening Guidelines	15
	2.3 Procedure for Assessing Techniques for Bottleneck Alleviation	18
	2.4 Other Considerations	29
3.0	SITE VISITS	30
	3.1 Site Selection	30
	3.2 Findings from the Site Visits	30
	3.2.1 San Diego Area Sites	33
	3.2.2 Los Angeles Area Sites	33
	3.2.3 San Francisco Area Sites	37
	3.2.4 Minneapolis Area Sites	44
	3.2.5 Houston Area Sites	44
	3.2.6 Washington D.C. Area Sites	44
	3.3 Conclusions	49
4.0	EVALUATION PROCEDURES	51
	4.1 Modeling and Metering Design Issues	51
	4.2 Estimation of Origin-Destination Demand Volumes	52
	4.2.1 Details of Modified Proportional Assignment Method	52
	4.2.2 Example Application of Procedure for Estimation of Origin-Destination Demand Volumes	53
	4.3 Metering Design and Evaluation	54
	4.3.1 Modeling and Metering Design Principles	54
	4.3.2 Overview of the Metering Design and Evaluation Procedure	55
	4.3.3 Details of Metering Design Procedure	55
	4.3.4 Short Trip Diversion	59
	4.3.5 Use of the Metering Design and Evaluation Procedure to Measure Impacts of Freeway Congestion	61
	4.3.6 Example Application of Metering Design and Evaluation Procedure	63
5.0	EVALUATION RESULTS	65
	5.1 Characteristics of Sites Evaluated	65
	5.2 Analysis Approach	65
	5.3 Site-Specific Evaluation Results	71
	5.4 Conclusions	88

BEST DOCUMENT AVAILABLE

TABLE OF CONTENTS
(Continued)

Section		Page
6.0	SCENARIOS FOR SIMULATION	89
	6.1 Objectives and Applications of Simulations	89
	6.2 Simulation Scenario Data	90
	6.3 Design of Experiments	112
	6.3.1 Downstream of Interchange	112
	6.3.2 Upstream of Interchange	112
	6.3.3 Interchange Subsystem	112
7.0	REFERENCES	113
	APPENDIX A	114

BEST DOCUMENT AVAILABLE

LIST OF FIGURES

Figure		Page
1	San Francisco/Oakland Bay Bridge Access Control	4
2	View of Metering Operation for Access to the San Francisco/Oakland Bay Bridge	5
3	Planned Connector Metering on San Diego/Harbor Freeway Interchange in Los Angeles	7
4	Advance Warning and Carpool Lane Signing for a Connector Metering Implementation in the San Diego Area [CALT78]	8
5	Advance Warning Sign for a Connector Metering Implementation in the San Diego Area [CALT78]	9
6	Connector Metering Installation in San Diego	10
7	Route 94 in San Diego	17
8	I-395 (Shirley Highway)	17
9	Route 59 (Southwest Freeway) in Houston	19
10	Procedure for Assessing Techniques for Bottleneck Alleviation	20
11	Analysis of Bottlenecks Downstream of an Interchange	18
12	Detailed Procedure for Assessing Techniques for Bottleneck Alleviation	21
13	Network Representation of Route 94, Westbound Site in San Diego	23
14	Hypothetical Trip Length Distribution	27
15	Six Metropolitan Areas Visited	31
16	Connector Metering at the Interchange of Route 94 and Route 125 in San Diego (Site S-3)	34
17	Connector Metering at the Interchange of Route 15 and Route 94 in San Diego (Site S-1)	35
18	Los Angeles Area Sites	36
19	Candidate Mainline Metering at Interchange of San Diego and Santa Monica Freeways in Los Angeles (Site LA-2)	38
20	Location of SF-2 Site (Route 24/I-580 Interchange)	39
21	Location of Site SF-4 in San Jose	40
22	SF-2 Site with Possible Mainline Metering at Route 24 Interchange	42
23	Route 17 in San Jose Containing Site SF-4	43
24	Location of Sites Visited in the Minneapolis Area	45
25	Houston Area Sites	46
26	Location of Capitol Area Sites	47
27	Merge Area of George Washington/Spout Run Parkways (Site CA-1)	48
28	Notation for OD Estimation	52
29	Schematic and Data for Example	53
30	Flow Diagram for Metering Rate Design and Performance Evaluation	56

BEST DOCUMENT AVAILABLE

LIST OF FIGURES
(continued)

Figure		Page
31	Technique for Considering Mainline Metering	55
32	Notation for Metering Rate Assignment	57
33	Short Trip Diversion	60
34	Notation for Short Trip Diversion Computations	60
35	Effects of Congestion	62
36	Shift of On-Freeway Queueing to Access Queueing	62
37	Accumulation of Excess Demand	63
38	Network Representation of Route 94, Westbound Site in San Diego	66
39	Network Representation of I-10, Eastbound Site in Los Angeles	67
40	Network Representation of I-35W, Southbound Site in Minneapolis	68
41	Network Representation of Route 59 (Southwest Freeway), Inbound Site in Houston	69
42	Network Representation of I-395 (Shirley Highway), Inbound in Virginia	70

BEST DOCUMENT AVAILABLE

LIST OF TABLES

Table		Page
1	General Guidelines for Screening Candidate Sites for Connector and/or Mainline Metering	13
2	Factors Influencing Effectiveness of Redesign and/or Control Downstream of an Interchange	13
3	Factors Influencing Effectiveness of Redesign and/or Control Upstream of an Interchange	16
4	Factors Influencing Effectiveness of Redesign and/or Control Upstream within an Interchange	16
5	Demand/Capacity Analysis	24
6	Assessment of Storage Capabilities for Metering Options	25
7	Assessment of Diversion Potential for Combined Ramp and Connector Metering	28
8	Summary of Candidate Site Characteristics	32
9	Estimated Origin-Destination Volumes for Example	54
10	Data Inputs for Example Application of Metering Design and Evaluation Procedure	63
11	Results of Example Application of Metering Design and Evaluation Procedure	64
12	Metering Design and Evaluation Results for Route-94, Westbound in San Diego	72
13	Metering Design and Evaluation Results for I-10, Eastbound in Los Angeles	75
14	Metering Design and Evaluation Results for I-35W, Southbound in Minneapolis	79
15	Metering Design and Evaluation Results for Route 59 (Southwest Freeway), Inbound in Houston	82
16	Metering Design and Evaluation Results for I-395 (Shirley Highway), Inbound in Virginia	85
17	Organization of Simulation Scenario Data	90
18	Geometric and Constraint Data for I-15 Westbound in San Diego	91
19	Traffic Demand Data for Route 94 Westbound in San Diego	92
20	Entrance/Exit Volume Data for Route 94 Westbound in San Diego	93
21	Ramp and Connector Metering Plan, with Associated Queueing and Diversion for Route 94 Westbound in San Diego	94
22	Geometric and Constraint Data for I-10 Eastbound in Los Angeles	96
23	Traffic Demand Data for I-10 Eastbound in Los Angeles	97
24	Entrance/Exit Volume Data for I-10 Eastbound in Los Angeles	98
25	Ramp and Connector Metering Plan, with Associated Queueing and Diversion for I-10 Eastbound in Los Angeles	99
26	Geometric and Constraint Data for I-35W Southbound in Minneapolis	100
27	Traffic Demand Data for I-35W Southbound in Minneapolis	101
28	Entrance/Exit Volume Data for I-35W Southbound in Minneapolis	102

BEST DOCUMENT AVAILABLE

LIST OF TABLES
(continued)

Table		Page
29	Ramp and Connector Metering Plan, with Associated Queueing and Diversion for I-35W Southbound in Minneapolis	103
30	Geometric and Constraint Data for Route 59, Inbound in Houston	104
31	Traffic Demand Data for Route 59, Inbound in Houston	105
32	Entrance/Exit Volume Data for Route 59, Inbound in Houston	106
33	Ramp and Mainline Metering Plan, with Associated Queueing and Diversion for Route 59, Inbound in Houston	107
34	Geometric and Constraint Data for I-395 (Shirley Highway), Inbound in Virginia	108
35	Traffic Demand Data for I-395 (Shirley Highway), Inbound in Virginia	109
36	Entrance/Exit Volume Data for I-395 (Shirley Highway), Inbound in Virginia	110
37	Ramp and Mainline Metering Plan, with Associated Queueing and Diversion for I-395 (Shirley Highway), Inbound in Virginia	111
38	Treatment Downstream of Interchange	112
39	Treatment Upstream of Interchange	112

BEST DOCUMENT AVAILABLE

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This report includes, as Appendix A, a report entitled, "Summary of Freeway-to-Freeway Ramp Control Installations," authored by Mr. Glen Carlson and Mr. Stu Harvey.

1.0 INTRODUCTION

The freeway systems across our nation have reached a substantial level of maturity in terms of basic facilities; little additional major construction can be anticipated. Responding to the needs of the public, freeway operations personnel have experimented with and implemented a variety of TSM tactics, notably electronic surveillance and incident detection, ramp metering, and various forms of high occupancy vehicle techniques. These are now mature traffic engineering tactics. Success with such tactics has served to expose remaining operational problems.

Even with the application of ramp metering, bottlenecks remain on urban freeways. In the few locations where actual implementations have been made, the techniques of control of mainline flow and freeway-freeway connector flow by use of traffic signals have proven to be effective.

The objective of this study was to explore these two relatively untried techniques, mainline and connector metering, in order (1) to arrive at useful guidelines for operational agencies which can aid them in identifying sites for which such techniques are appropriate, and (2) to provide guidance in the design of metering techniques and associated signing.

There appear to be many special situations for which mainline metering could have benefit. One class of such situations is accesses to tunnels and bridges. The San Francisco/Oakland Bay Bridge facility is a good example of the application of mainline metering. Benefits in this instance include:

(1) Elimination of congestion on the bridge; and

(2) Allocation of access to the bridge to provide congestion-free access for High-Occupancy-Vehicles, thereby decreasing passenger delay and encouraging shifts to HOV modes.

Additionally, the Port of New York Authority has for many years successfully operated access control for tunnels in the New York area [FOOT74]. A second class of situations occurs where, despite the application of ramp metering, lack of control of the traffic stream upstream of the controlled segment, combined with a steady growth in traffic demand, has led to steady deterioration of the level of service and of effectiveness of ramp metering. Direct control, obtained by metering of the mainline at an appropriate location, appears to be a potentially effective remedy. There are at present no implementations of mainline metering of this sort (except for a manual metering implementation on the George Washington Parkway in the Washington, D.C. area).

Potential benefits include:

(1) Better access for High-Occupancy-Vehicles (if an HOV lane and preferential metering were implemented),

(2) Improved flow through the bottleneck area on the mainline, with attendant increases in traffic volume,

(3) Improved effectiveness of ramp metering downstream of the mainline metering location, particularly at high demand ramps,

(4) Improved equity amongst drivers along the corridor, and

(5) Better utilization of the corridor because of diversion to good alternate street routes.

A third significant class of problems is congestion associated with major freeway-to-freeway interchanges. Uncontrolled traffic flow on freeway-to-freeway connectors can create excessive demand in merging areas which leads to congestion on the mainline of the freeways. This problem has been successfully addressed in several areas by implementing metering on the connectors. Implementations currently exist in San Diego and Minneapolis.

Potential benefits include:

(1) Displacement of queueing from the mainline to connectors, providing a consistent, controlled traffic situaion with better safety characteristics,

(2) Improved flow through the bottleneck area on the mainline, with attendant increases in traffic volume,

(3) Avoidance of less efficient metering of on ramps upstream of the freeway-to-freeway interchange,

(4) Improved equity amongst drivers along the corridor, and

(5) Diversion of connector traffic to alternate routes to provide better utilization of the freeway corridor.

The principal thrust of the study that was undertaken and is reported upon here is an examination of the techniques of mainline and freeway-to-freeway connector metering that took two forms: (1) site visits to locations with actual implementations, plans, or which have potential for implementation; and (2) analytical case studies for the purpose of providing quantitative measures of expected performance. Jointly, these examinations were then used to develop guidelines for determining situations in which such control techniques might be operationally effective.

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The project effort was organized into four tasks. The first two tasks involved information gathering. In the first of these, available literature was reviewed for material relevant to this project. The most significant item of available literature is a report entitled "Summary of Freeway-to-Freeway Ramp Control Installations", prepared for the Freeway Operations Committee of the Transportation Research Board [CARL80]. This report documents the implementation of and operational experience pertaining to connector metering in San Diego and Minneapolis. It has been included in this report as Appendix A.

The second information-gathering task involved visits to sites with associated discussions with operational personnel. Visits to fifteen distinct sites in six different metropolitan areas were undertaken. These sites included representatives of existing freeway-to-freeway connector metering (San Diego and Minneapolis), an existing bridge access metering site (San Francisco/Oakland Bay Bridge), and an existing manually metered mainline site (George Washington/Spout Run Parkways in the Washington, D.C. area). Remaining sites were representative of candidates for connector and mainline metering.

The purpose of these site visits was to extract valuable experiential knowledge of existing implementations, and aspects of traffic situations relevant to successful implementations. Further, data pertinent to specific sites served as representative cases for subsequent analysis and illustrations of procedures.

The analytical effort was undertaken in the third task. The major elements of this task were (1) development of analytical procedures, (2) analysis and assessment of mainline and connector metering, and (3) development of implementation guidelines.

The single most important product of this effort is the set of user-oriented guidelines for implementation of mainline and connector metering. These guidelines provide means for screening traffic situations for potential application of metering, details of implementations, and simple methods for predicting expected impacts.

The supporting analyses are presented in Sections 4 and 5. Principles and details of the metering design and evaluation procedures which were developed for use in this study are presented in Section 4. While the principal purpose of their development was to provide a means for assessing the value of mainline and connector metering, it is believed that the techniques themselves constitute important contributions to traffic engineering. In Section 5, detailed evaluations of mainline and connector metering, based on the procedures of Section 4 and applied to five representative cases, are presented. These cases were extracted from data obtained as part of the site visit activity, and therefore represent actual traffic situations.

The final task, consisting of the development of simulation scenarios, was intended to provide a bridge to future research in which simulation models will be used to thoroughly analyze mainline and connector metering, and to investigate effects not represented in the analytical procedures developed and used in this project. detailed input data suitable for use in the dynamic simulation models FREQ [JOVA78], FREFLO [PAYN78] and/or INTRAS [WICK77] are presented in Section 6.

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2.0 GUIDELINES PERTAINING TO THE IMPLEMENTATION OF CONNECTOR AND MAINLINE METERING

The purpose of this section is to provide to operational personnel information concerning the implementation of connector and mainline metering in several forms:

(1) Information pertaining to implementation of metering signals and advanced warning signs,

(2) Factors of the traffic situation which influence the suitability of implementing connector and/or mainline metering,

(3) Guidelines which are sufficient to identify sites where such implementation may be beneficial,

(4) Procedures for resolving the type of treatment appropriate to a site, and

(5) Procedures for estimating the expected impacts of a selected treatment.

As a preliminary the first subsection which follows describes the traffic situations for which these guidelines are intended, and introduces mainline and connector metering techniques as methods for dealing with certain instances of congestion. Additional details of implementation for connector metering are provided in Appendix A [CARL80].

Subsection 2.2 deals with items (2) and (3) cited above. General guidelines and example applications are provided there.

Items (4) and (5) are addressed in Subsection 2.3. General quantitative procedures with examples are provided.

The final subsection presents additional considerations, especially as pertaining to the public acceptance of these new forms of metering.

This section is intended to be self-contained for the purposes indicated. The remaining sections of this report may be of interest to operational personnel who wish to examine in detail the basis for the information provided here.

2.1 Traffic Control Treatments

Traffic control, effected by metering traffic through the use of traffic signals and with associated warning flashers and signs, has been applied to tunnel and bridge bottlenecks, freeway-to-freeway interchange bottlenecks, and other mainline freeway bottlenecks. Here, the available traffic control treatments are identified and the expected benefits and impacts are indicated as they apply to each of these traffic situations.

2.1.1 Metering of Access to Tunnels and Bridges

The traffic situation at bridge and tunnel entrances exemplifies a general class of traffic situations in which there exists a peak demand in excess of the capacity of a "point" facility. Prominent characteristics of this class are:

(1) limited alternatives in terms of spatial diversion, i.e., choice of an alternate route;

(2) tendency for congestion to occur on the facility, especially on upgrades which are often involved; and

(3) existing means or good opportunity for access control.

The example of the San Francisco/Oakland Bay Bridge illustrates many common points. As is clear from Figure 1, there is little route choice for commuters travelling from the Oakland area to San Francisco. Options for commuters do include temporal diversion (travelling at a different time, to avoid severe congestion), and a mode shift to car pooling, van pooling or BART (Bay Area Rapid Transit).

Total vehicular demand in the AM peak period for the westbound SF/Oakland Bay Bridge exceeds capacity, and (prior to control treatment) had led to congestion on the upgrade to the elevated bridge structure. Tolls are collected at the east entrance (i.e., for westbound traffic) in an area that has ample storage for the excess demand.

The problems associated with tunnel and bridge bottlenecks can be addressed by metering the access to the facility. Part or all of the traffic stream can be controlled to achieve entrance volumes which can be handled by the facility without leading to congestion.

Such control will move the congestion from the bottleneck on the facility to the area upstream of the metering location. This in itself can have safety benefits related to the fact the queue is moved to a location where motorists can be prepared for its presence, e.g., through the use of advance warning techniques. Further, in the instance of the Holland tunnel [FOOT74], it was observed that throughput improvements were also achieved. Such access control also gives rise to an opportunity to use preferential access for high occupancy vehicles (HOVs). HOVs can be provided special access lanes so that all (or most of) the queueing delay is borne by non-HOVs. This leads directly to reductions in passenger travel time, and encourages shift to HOV modes.

Metering is typically accomplished by the use of traffic signals placed over the traffic lanes (see Figure 2). The specifics of the metering procedure depend upon the volumes to

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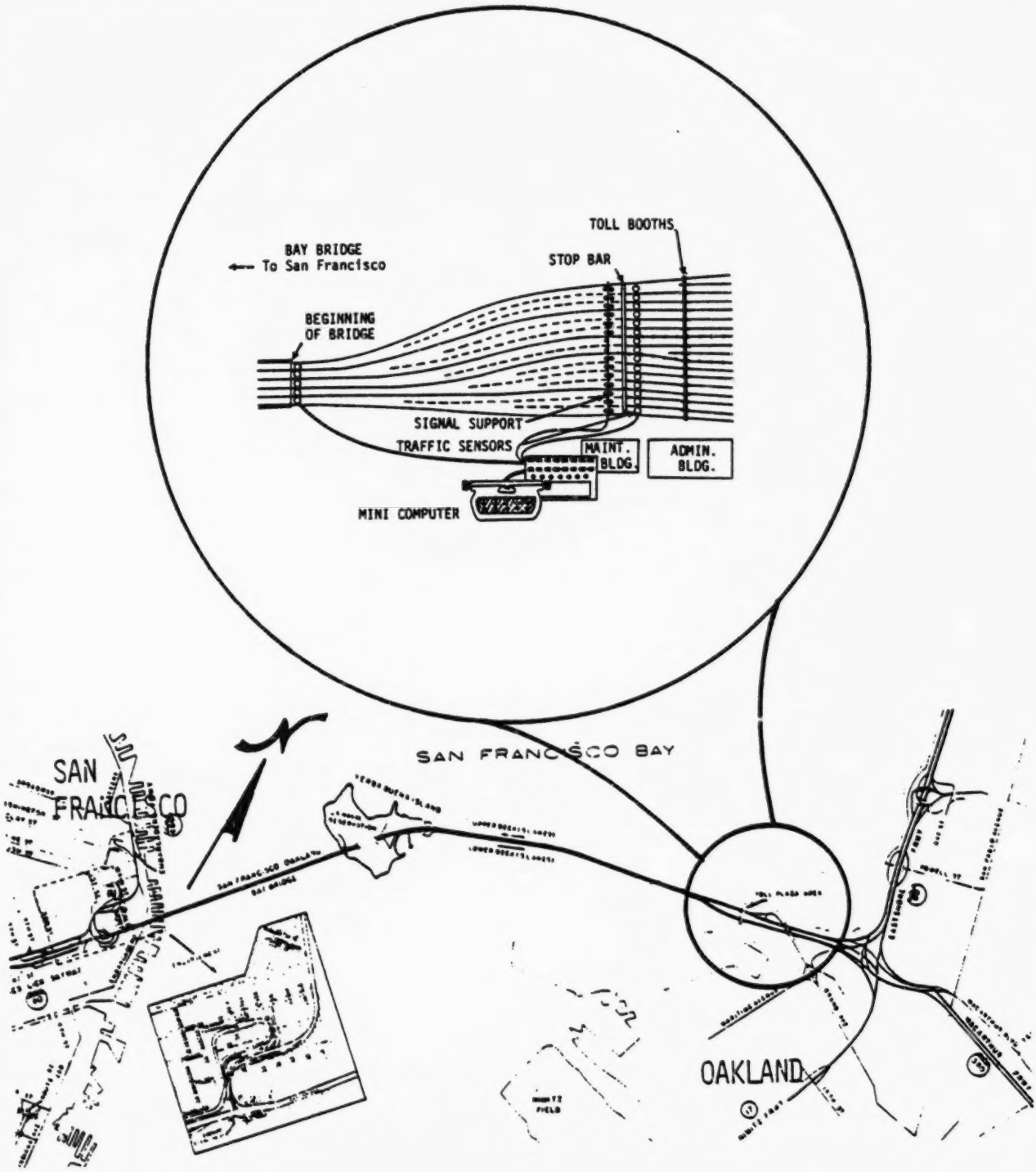

Figure 1. San Francisco/Oakland Bay Bridge Access Control

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Figure 2. View of Metering Operation for Access
to the San Francisco/Oakland Bay Bridge

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be accommodated and the policies concerning HOVs. Metering techniques include:

(1) one-at-a time,
(2) two-at-a time, and
(3) platoon metering.

The choice relates directly to the volume which it is desired to achieve by metering. One-at-a time metering provides the most discipline, but it provides an upper bound of around 900 vehicles per hour per lane (4 seconds per cycle) before erratic response results. If higher volumes (per lane) are required, two-at-a time or platoon metering must be used. An alternative is to provide more lanes.

The collection of metering rates must be set to limit vehicular access to a level which the facility can handle without "breakdown" and concomitant congestion. The simplest technique for achieving this is to set the sum of the metering rate and the upstream mainline volume to a value somewhat less than the bottleneck capacity. More sophisticated techniques, such as employed on the San Francisco/Oakland Bay Bridge facility, account for the type of vehicle (e.g., trucks have a passenger car equivalent of between 2 and 5), and continuously monitor the input traffic stream and the traffic condition on the bridge so that adjustments to the metering rates may be made to fully utilize available capacity while avoiding congestion.

Where HOV preference is to be provided, separate HOV-only access lanes must be provided. The HOV access lane may or may not be subject to metering. However, it is necessary to account for the HOV demand in specifying details of the metering rates.

Typically, there will be high-speed approaches to the metering location. This may necessitate the implementation of advance warning flashers and or signs, recognizing the variable length of the queue.

2.1.2 Freeway-to-Freeway Connector Metering

The complex geometries and multiplicity of merges of high-volume roadway segments often involved in urban freeway-freeway interchanges leads to many instances of congestion, both on the mainline and on the connectors between freeways.

Typical of this class of traffic situations are:

(1) high volume connectors which, together with the mainline volumes, involve demands on merge areas in excess of capacity immediately downstream of the merge area;

(2) queueing on the mainline, which may backup to interfere with upstream exit movements;

(3) queueing on the connectors, which may backup to and interfere with traffic flow on the feeding freeway; and

(4) in some instances, additional mainline congestion at other interchanges in the freeway segment.

In a number of instances, ramp metering in the freeway segment already exists. Availability of reasonable alternate routes around the freeway-to-freeway interchange varies between locations. Figure 3 illustrates one such instance, the interchange of the San Diego and Harbor freeways in Los Angeles.

This example illustrates several common points. Ramp metering has been operational on the northbound San Diego freeway downstream of this interchange for many years, and was initially successful in eliminating congestion on the freeway. As vehicular demand grew, on ramp metering rates were adjusted but the growth in demand at the interchange was uncontrolled, and eventually, congestion returned to the freeway. In particular, the high volume connectors carry an excess of demand onto the freeway and cause congestion immediately downstream of the interchange.

Operational bottlenecks associated with freeway-freeway interchanges can be relieved by metering high-volume connectors, and/or by mainline metering. Here, we restrict ourselves to connector metering, leaving mainline metering to the next section.

Connector metering moves the congestion from the mainline freeway or upstream metered on ramps to the connector. If appropriate advance warning is provided to the connector traffic and queues do not extend into through traffic on the crossing freeway, this can lead to safety improvements. HOV treatments can be applied at the metering location to provide passenger travel time benefits. Figures 4 and 5 illustrate the use of advance warning signs in the San Diego area. Figure 4 also illustrates the use of an HOV treatment (for carpools). By maintaining uninterrupted flow conditions on the mainline freeway, full geometric capacities are realized. Diversion of connector traffic may occur and lead to further travel time benefits.

Metering is typically accomplished by the use of a pair of traffic signals placed on either side of the connector. The options of one-at-a-time, two-at-a-time and platoon metering are available to yield the required range of metering rates. Figure 6 illustrates a connector metering installation in San Diego.

A report entitled, "Summary of Freeway-to-Freeway Ramp Control Installations", prepared for the Freeway Operations Committee of the Transportation Research Board [CARL80] documents the implementation of connector metering in San Diego and Minneapolis. (It is included as

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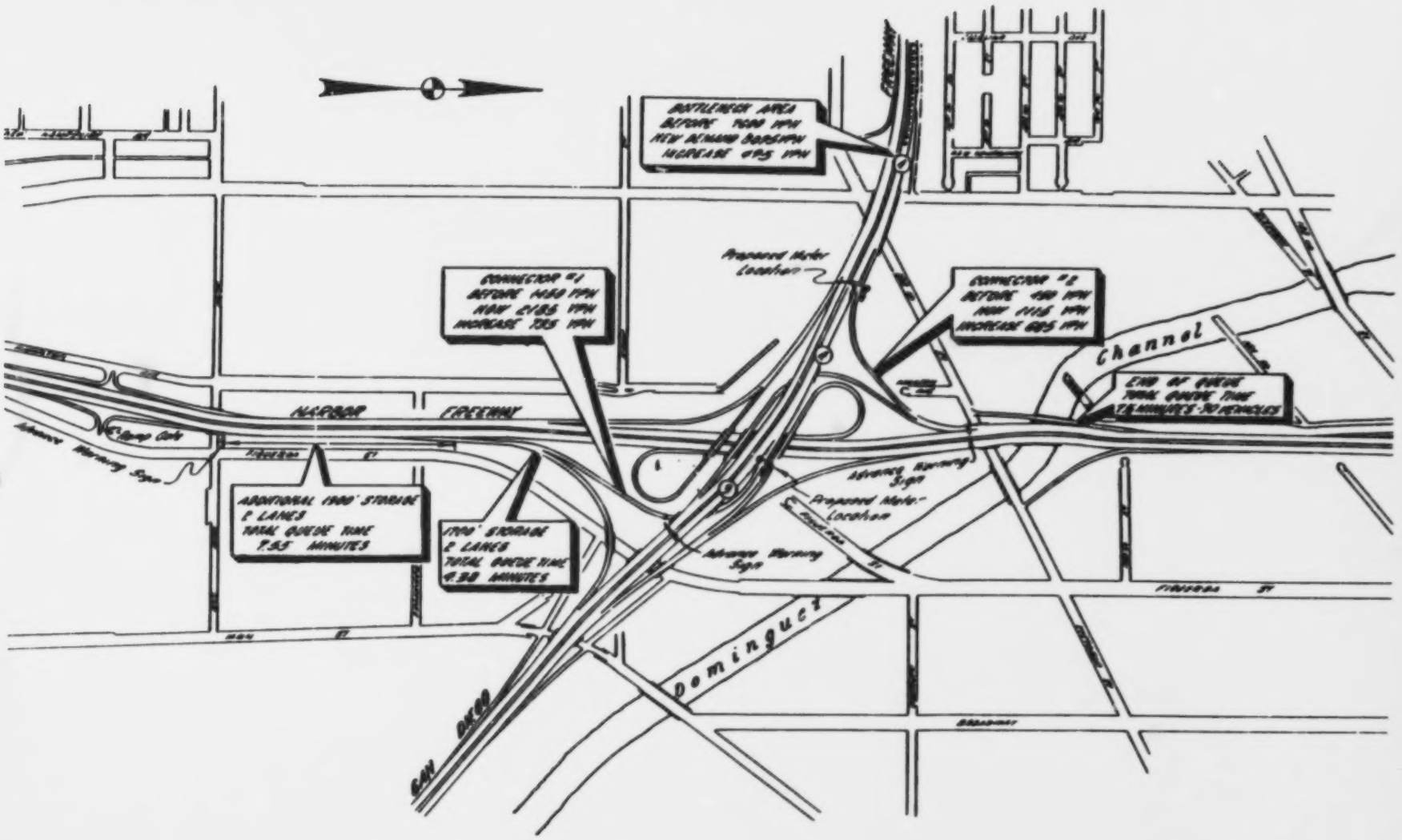

Figure 3. Planned Connector Metering on San Diego/Harbor Freeway Interchange in Los Angeles

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Figure 4. Advance warning and carpool lane signing for a connector metering implementation in the San Diego Area [CALTRA]

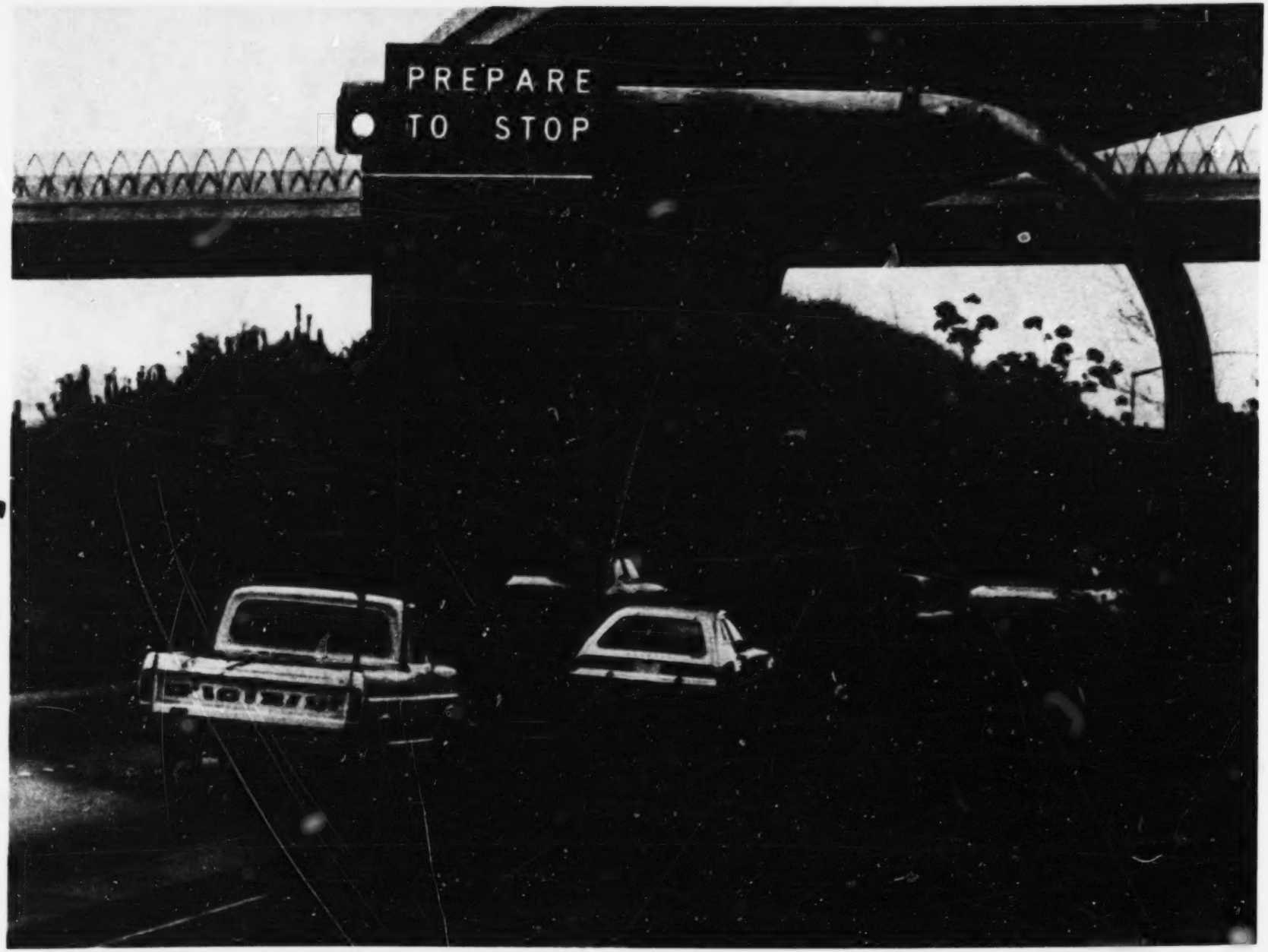

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Figure 5. Advance Warning Sign for a Connector Metering Implementation in the San Diego Area ([CALT78])

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Appendix A of this report.) This report contains important details concerning the placement of metering signals and advanced warning signs, and the manner of operating metering signals. Operational experience is also documented.

The queues which are created by connector metering require particular attention. They can grow to such length that they impede traffic on the crossing freeway. This could negate any travel time benefits otherwise obtained and may create a serious traffic hazard. This potential problem can be addressed by restriping and/or reconstruction to provide more storage, operational procedures (e.g., closing a nearby ramp) to reduce weaving through the queue, and by queue override techniques which have been used for on-ramp metering [KOBL80]. The latter technique involves real-time measurement of the queue length, and a responsive metering implementation which can open up metering as necessary to avoid having undesirable queue growth.

Connector metering is generally a part of a larger metering system, including the metering of adjacent on ramps. Thus, design of the metering plan for a connector must be integrated into a system metering plan. For example, a fixed-time plan must account for: (1) demands at the upstream end of the freeway, at the connector(s) and at the on ramps; (2) expected queues at metering locations vis-a-vis available storage; and (3) expected diversion. Traffic responsive metering is also an important option (but is not explicitly considered here).

2.1.3 Metering of Mainline Traffic

Mainline freeway congestion occurs whenever the total demand exceeds the location-specific capacity. One can distingush

(1) geometric bottlenecks, where local geometrics such as upgrades, curves, or restricted vision yield a diminished capacity; and

(2) operational bottlenecks, where total demand consisting of mainline and entrance ramp demands exceed capacity immediately downstream of the merge area.

General features involved in mainline freeway bottlenecks are:

(1) queueing on the mainline, which may backup to restrict egress from the mainline at one or more off ramps; and

(2) in many instances, accumulation of demand over many miles upstream of the bottleneck location associated with on ramps demands in excess of off ramp volumes (e.g., AM traffic on a freeway segment directed toward a CBD)

Availability of reasonable alternate routes around the bottleneck varies amongst facilities.

In some instances, for example the Southwest Freeway in Houston, there is an existing ramp metering system which was implemented to control the accumulation of excess demand. However, the continual growth in uncontrolled upstream demand can (and has in the Houston facility cited) overwhelmed the ability of the ramp metering system to avoid mainline congestion.

Mainline metering has been suggested as a technique to alleviate freeway-freeway interchange bottlenecks, possibly with associated connector metering; and where there is a geometric or operational bottleneck (not related to freeway-freeway interchange), and a heavy mainline demand. In traffic engineering terms, mainline metering is conceived to be quite similar to the control of access to tunnels and bridges, and would share many of its attributes: (1) move congestion to the area immediately upstream of the metering location, with possible safety benefits; (2) possess options for metering tactics, including one-at-a-time, two-at-a-time and platoon metering; (3) allow application of HOV treatments; (4) involve traffic signals mounted overhead; and (5) require advance warning signs. The discussions pertaining to metering of access to tunnels and bridges, and Appendix A, which describes connector metering implementations, contain information relevant to design of mainline metering.

Advocates of mainline metering say that implementation should be made only where there is an existing queue on the freeway. Hence, mainline metering would be introduced to manage the on-freeway congestion. This attitude reflects a proper concern for safety and likely public response to an implementation of mainline metering.

If implemented, mainline metering may be part of a metering system in which on ramps are also metered. Issues of bottleneck capacity, storage at the mainline and on-ramp metering locations and expected diversion are all relevant. The extent of the queue will be of particular significance since warning signs should be placed in advance of the tail of the queue. Further, a queue which obstructs egress from the freeway will produce related travel time disbenefits.

2.2 Assessment of Applicability of Connector and Mainline Metering

The purpose of this section is to assist operational personnel in assessing the applicability of connector and mainline metering to specific candidate sites. First, we indicate and discuss those factors of a site which influence the suitability of implementing such metering. Next, we present general guidelines for screening candidate sites in tabular form based upon certain of

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those factors, and illustrate their use. Finally, we present a procedure for examining a site for the purpose of determining the appropriate type of treatment.

2.2.1 Assessment Factors

The three most important factors to be considered are (1) the relationship of the traffic demand to the freeway capacity, (2) the available storage at metering locations, and (3) the quality of the alternate route.

Traffic Demand

Freeway congestion will result if traffic demand which is in excess of freeway capacity is allowed to enter the freeway. The degree of excess demand and the specific location of bottlenecks can be determined by observation of existing conditions. Simple computations using entrance and exit volume data and estimates of freeway capacities at key locations can also be made. Three regimes of relative traffic demand are distinguished here:

(1) Slight excess in traffic demand: Queueing at bottlenecks is "localized" in the sense that queues do not extend upstream beyond any exit.

(2) Moderate excess in traffic demand: Queueing associated with one or more bottlenecks is sufficient to extend upstream beyond one or more exits, but the freeway is not completely involved in congestion.

(3) Heavy excess in traffic demand: The freeway is completely involved in congestion for some portion of the peak period.

A more subtle but equally important aspect of the traffic demand is the trip pattern. Specifically, it is imortant to know the distribution of the demand at the bottleneck by entrance location, and the distributions of demand by destination at locations where metering may be applied. Metering is most effective where all or most of the metered traffic is destined for the bottleneck. Metering tends to be ineffective where a substantial fraction of the metered demand has destinations upstream of the bottleneck.

Available Storage

Metering can remove congestion from the freeway by storing or diverting enough vehicles at the metering locations to reduce the traffic volumes on the freeway to levels which do not exceed freeway capacity at critical (potential bottleneck) locations. As the accumulated excess in traffic demand over capacity at a bottleneck increases, the required storage/diversion at locations upstream of the bottleneck increases. Since storage at each metering location is limited, this tends to increase the number of locations at which metering is required. Where the total storage/diversion at on ramps is not sufficient to handle the peak accumulation in excess demand, connector and/or mainline metering may be necessary.

Quality of Alternate Route

The quality of the alternate route determines the attractiveness of diversion to drivers who are subject to delays at metering locations. A high speed alternate route would allow some drivers to divert from a queue at a metering location to the alternate and thereby achieve a travel time savings. Specifically, such savings occur where the trip is short enough that the travel time on the street is less than the travel time to the freeway, through the ramp queue, on the freeway, and, finally, away from the freeway. Where the alternate is poor, only drivers taking very short trips will find the alternate attractive. Since queue storage at metering locations is limited, the quality of the alternate route has a very substantial bearing on whether metering can be effectively applied. In particular, where there are poor alternates so that very little diversion can be anticipated, metering can only absorb an accumulated excess of traffic demand equal to the total available storage upstream of the bottleneck.

We distinguish three levels of quality of alternate routes:

(1) Poor: Typical speeds of 10 mph
(2) Good: Typical speeds of 25 mph
(3) Excellent: Typical speeds of 40 mph

2.2.2 Screening Guidelines

In Table 1, these factors are combined in tabular form to provide simple, general guidelines useful for screening candidate sites for connector and/or mainline metering. In using these guidelines, some impacts of metering which are generally present in any sort of metering system should be kept in mind. First, ramp metering smooths out the highly peaked demands associated with platoons entering the ramp from nearby signalized intersections. This has a very beneficial effect on the merge process, producing safety benefits, and possibly to some extent an increase in the capacity in the merge area. Second, metering systems, by removing even a modest amount of congestion from the mainline, may have substantial benefits in terms of freeway travel times. This will occur where the removal of congestion yields a significant increase in freeway capacity. There is some theoretical basis for expecting such an increase (e.g., theories which embody a discontinuity (discrete drop) in volume above a certain critical traffic density). Further, some operational traffic engineers indicate that their experience supports this. But there is no hard, scientific evidence available to firmly support this view (or to

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Table 1. General Guidelines for Screening Candidate Sites for Connector and/or Mainline Metering

<table>
<tr><th rowspan="2">Traffic Demand</th><th colspan="3">Quality of Alternate Route</th></tr>
<tr><th>Poor (10 mph)</th><th>Good (25 mph)</th><th>Excellent (40 mph)</th></tr>
<tr><td>Slight Excess Demand</td><td colspan="3">• On-ramp metering alone expected to alleviate freeway congestion
• Connector metering may be more appropriate where congestion is related to a connector merge
• Negligible travel time impacts</td></tr>
<tr><td rowspan="2">Moderate Excess Demand</td><td colspan="3">• On-ramp metering alone may be sufficient to alleviate freeway congestion
• On-ramp metering and metering of mainline and/or connector in the upstream proximity of the bottleneck is expected to alleviate freeway congestion</td></tr>
<tr><td>• Negligible travel time impact</td><td>• Moderate improvement in travel time</td><td>• Substantial improvement in travel time</td></tr>
<tr><td rowspan="2">Heavy Excess Demand</td><td rowspan="2">• No form of metering can avoid freeway congestion</td><td colspan="2">• On ramp and metering of mainline and/or connector necessary to alleviate freeway congestion</td></tr>
<tr><td>• Substantial improvement in travel time</td><td>• Very substantial improvement in travel time</td></tr>
</table>

Table 2. Factors Influencing Effectiveness of Redesign and/or Control Downstream of an Interchange

Downstream Subsystem Effective	Cost of Redesign Solution	Degree of Congestion	Number of Ramps in Subsystem	Attractive Alternate Routes	Concern for Equity
No	High	High	Small	Poor	High
Partial	Moderate	Moderate	Moderate	Moderate	Moderate
Yes	Low	Low	Large	Good	Low

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deny it, for that matter). Consequently, in the remainder of this report a conservative approach to travel time benefits has been taken by assuming that mainline freeway capacity improvements do not result from removing congestion from the freeway.

Referring to Table 1, it is seen that where the traffic demand is only slightly in excess of freeway capacity, on-ramp metering alone can be expected to alleviate freeway congestion. Where freeway congestion is associated with connector merging, connector metering can be expected to be effective. Travel time impacts are very small, so that benefits are limited to improved safety.

Even with moderate traffic demand levels, ramp metering alone may suffice, but sufficiently large mainline and/or connector volumes will dictate the use of mainline and/or connector metering at those locations. In this circumstance, the quality of the alternate route directly affects the resultant travel time benefits. Where the alternate is poor, impacts on travel time are slight (and may even represent disbenefits); where the alternate is good, moderate improvements in overall travel time are to be expected; and where the alternate is excellent, substantial improvements are to be expected.

With yet greater traffic demand, the ability of metering to alleviate freeway congestion becomes stressed. If the alternate route is poor, heavy excess traffic demands cannot be handled with any form of metering as essentially all vehicles queue at metering locations, leading to queue growth that exceeds available storage. With a better alternate, the combination of long delays at metering locations and a reasonable alternate route causes many drivers to divert to the alternate. This allows a system with on-ramp and connector and/or mainline metering (everything available upstream of a bottleneck will be needed) to alleviate the freeway congestion. Travel time benefits are substantial to very substantial.

One final general comment is in order here. As traffic demands have grown in metropolitan areas, a situation has been reached in many instances were ramp metering alone cannot successfully remove freeway congestion while, at the same time, respecting queue storage constraints at these metering locations. The response on the part of operational personnel has been to use ramp metering to limit access, observe ramp queue storage limits, and put up with some level of congestion on the freeway. Metering rate design procedures for these circumstances are not well established, nor is there available information concerning related travel time impacts. As a result, where metering (including connector and mainline) cannot be expected to both eliminate freeway congestion and keep queues at metering locations within an area which avoids conflicts with other traffic, the guidelines we have provided merely indicate that "no form of metering can avoid freeway congestion".

The single most important traffic situation where connector and/or mainline metering may be applied is a bottleneck related to traffic entering from a freeway-to-freeway interchange. The next subsection deals with this specific situation.

2.2.3 Factors Affecting the Success of Re-Design/Control for Freeway-to-Freeway Interchange Related Bottlenecks

The most promising sites for mainline/connector control will be at interchanges just upstream of severe bottlenecks. The degree of success of mainline/connector control is influenced by many factors. One way of identifying and evaluating these factors is to divide the site into three subsystems: (1) downstream of interchange, (2) upstream of interchange, and (3) within the interchange. The following three paragraphs attempt to identify and evaluate primary factors in terms of these three subsystems.

Downstream of Interchange -- The premise is that mainline/connector control will not be required (or if attempted, not cost-effective) if redesign and/or control downstream of the interchange can effectively solve the problem. The cost effectiveness of solving the problem by concentrating on the subsystem downstream of the interchange is a function of (1) cost of redesign solution or partial solution, (2) the degree of congestion (the demand/capacity ratio), (3) the number of ramps between the interchange and the bottleneck, (4) the availability of attractive alternate routes, and (5) equity considerations.

Table 2 indicates that redesign and/or control downstream or the interchange can be most cost-effective when the cost of redesign solutions are low, the degree of congestion is low, the number of ramps is large, the alternative routes are good, and concern for equity is low. When three or more of these factors are not true, redesign and/or control in the interchange or upstream of the interchange should be considered. Current practice is to give next attention to the subsystem upstream of the interchange and postpone the consideration of redesign and/or control within the interchange.

Upstream of Interchange -- When redesign and/or control downstream of the interchange is insufficient, consideration is given to controlling the subsystem upstream of interchange. In normal interchanges, three roadways (the mainline and two connectors) feed the subsection downstream of the interchange. The cost-effectiveness of assisting in the solving of the downstream bottlenedk by controlling the roadways upstream of the interchange is affected by a

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number of factors. The primary factors appear to be: (1) ease of solving problems by actions in downstream subsystem, (2) willingness to redesign and/or control within the interchange, (3) proportion of upstream traffic passing through bottleneck, (4) current or planned control on upstream roadway(s), and (5) the availability of attractive alternate routes.

Table 3 indicates that control upstream of the interchange can be most cost-efective when the problem cannot be solved by actions in the downstream subsystem, there is little willingness for interchange measures, there is a high proportion of upstream traffic passing through the downstream bottleneck, the upstream roadway is currently being controlled already, and the alternate routes are good. The most critical factor is the proportion of upstream traffic passing through the bottleneck. Attention should be directed toward the interchange subsystem under two major conditions: (1) if the proportion of upstream traffic passing through the bottleneck is low, or (2) if the proportion of upstream traffic passing through the bottleneck is moderate, upstream control is not presently in operation or planned, and there is some willingness for interchange measures.

Interchange Subsystem — Consideration should be given to interchange measures when redesign and/or control downstream of the interchange is insufficient and control upstream of the interchange is not effective. One possible, but usually unattractive alternative, is to reduce the capacity of the mainline and/or connector(s) within the interchange. This is accomplished by narrowing lanes or reducing the number of lanes. Politically it may be relatively easy to implement but has the disadvantage of 24 hour per day operation and less flexible control of queue lengths. The other alternative is to control the mainline and/or connector(s) with the interchange. The cost effectiveness of assisting in the solving of the downstream bottleneck situation is affected by a number of fctors. The primary factors appear to be: (1) ease of solving problem by action upstream and upstream of interchange, (2) degree of willingness to control within the interchange, (3) approach speed to queueing process, (4) storage abilities for queueing process, (5) the availability of attractive alternative routes, and (6) equity considerations.

Table 4 indicates that control within the interchange can be most cost-effective when the problem can not be effectively solved by actions in the upstream and downstream subsystems, there is a willingness for interchange control, the approach speed to the queueing process is low, the storage for the queueing processs is adequate, the alternate routes are good, and concern for equity is high.

2.2.4 Example Applications of Screening Guidelines

To illustrate application of these screening guidelines, we shall consider three situations:

Example 1: Route 94 westbound in San Diego

Figure 7 is a map of the relevant area. The segment of concern extends from the Route 125/Route 94 interchange at the eastern end to the I-5/Route 94 interchange at the western end. Within this segment there are freeway-to-freeway interchanges with I-15 and I-805. In the absence of any metering, moderate levels of freeway congestion occur in the vicinity of the two freeway-to-freeway interchanges. There is also some light freeway congestion downstream of the Route 125/Route 94 interchange. Alternate routes are poor to good. Referring to the general guidelines of Table 1, the moderate levels of freeway congestion occuring near the eastern end of this segment may be successfully treated by ramp metering alone. However, it is possible that connector metering at the freeway-to-freeway interchanges in this vicinity may also be necessary. Some modest improvements in travel times are to be expected. For the congestion near the western end, congestion is related to the high volume connector demand, so that metering of the connector is most likely the appropriate treatment. Related travel time impacts will be negligible, however, since the principal effect of the metering is to move congestion from the freeway to a queue at the connector metering location.

Example 2: I-395 (Shirley Highway) northbound in Virginia

Figure 8 is a map of the relevant area. The segment of concern extends from Edsall at the southern (western) end to the 14th St. Bridge at the northern (eastern) end. Due to an accumulation of demand which is substantially in excess of the three lane capacity at Glebe Road, most of which enters at Shirlington, and since there are four lanes downstream of Globe Road, there is very heavy freeway congestion extending from Glebe Road upstream to Duke Street. Alternate routes are poor along this segment. Moreover, there is virtually no alternate to the 14th St. Bridge for drivers destined for Washington D.C. Referring to the general guidelines of Table 1, it appears that no form of metering can avoid freeway congestion. If ramp and/or mainline metering were to be applied, the heavy excess of traffic demand would lead to queues at metering locations (including the mainline) which could exceed available storage (depending, for example, on the location of the mainline meter). Note that if the alternate route were improved, at least in the Virginia area, a combination of ramp and mainline metering would very likely be successful and would then be expected to provide substantial travel time benefits.

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Table 3. Factors Influencing Effectiveness of Redesign and/or Control Upstream of an Interchange

No	Solvable	High	Low	Not Planned	Poor
Partial	Solvable But Difficult	Moderate	Moderate	Planned	Moderate
Yes	Not Solvable	Little	High	Current	Good
Upstream Subsystem Effective	Ease of Solving Problem Downstream	Willingness for Interchange Measures	Percent Upstream Traffic to Downstream Bottleneck	Current/ Planned Upstream Control	Attractive Alternate Routes

Table 4. Factors Influencing Effectiveness of Redesign and/or Control Upstream within an Interchange

No	Effective	Low	High	Not Adequate	Poor	Low
Partial	Marginal	Moderate	Moderate	Marginal	Moderate	Moderate
Yes	Not Effective	High	Low	Adequate	Good	High
Interchange Subsystem Effective	Ease of Solving Problem Up/Downstream	Willingness for Interchange Control	Approach Speed to Queue	Storage for Queue	Attractive Alternative Routes	Concern for Equity

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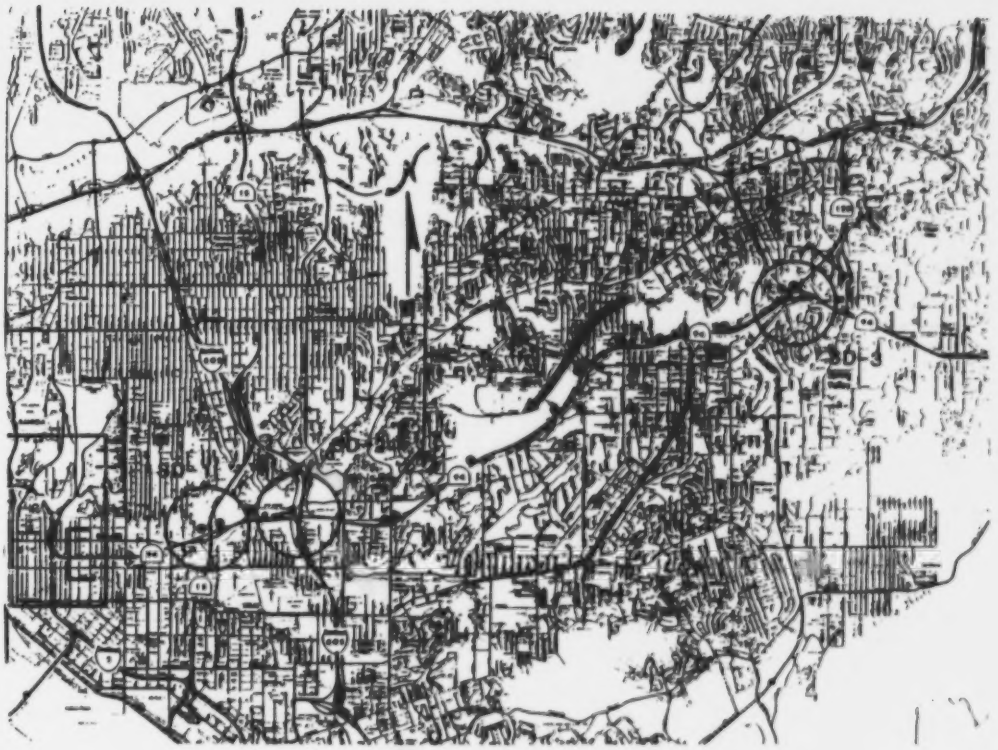

Figure 7. Route 94 in San Diego

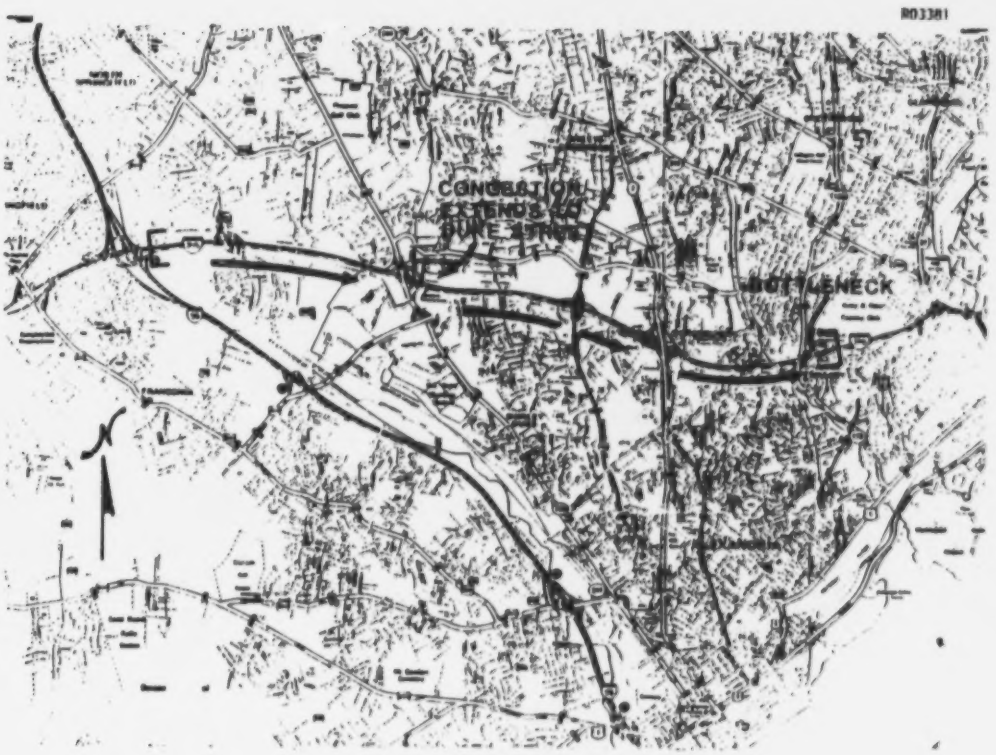

Figure 8. I-395 (Shirley Highway)

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Example 3: Route 59 (Southwest Freeway) Inbound in Houston

Figure 9 is a map of the relevant area. The segment of concern extends from Bissonnet at the southern end to the vicinity of the Central Business District at the downstream end. The bottleneck is upstream of the I-610/Route 59 freeway-to-freeway interchange, and is caused by an accumulation of demand in excess of the three lane capacity. Immediately downstream of the bottleneck, the freeway widens to four lanes. There is an existing ramp metering system extending along most of the length of this segment. Traffic demand is moderate to heavy, creating extensive congestion from the bottleneck upstream to the vicinity of Bissonnet. Alternates are good. Referring to the general guidelines, it appears that the addition of mainline metering to the existing ramp metering system could relieve the freeway congestion. Substantial travel time improvements are to be expected. Metering of the connector at the interchange with I-610 is not appropriate since this connector is downstream of the bottleneck.

2.3 Procedure for Assessing Techniques for Bottleneck Alleviation

Application of the screening guidelines will have indicated whether connector and/or mainline is a potential candidate for a particular site. The purpose of the procedure detailed here is to direct a potential implementor through a series of assessments which will resolve in a finer way what technique for bottleneck alleviation is most appropriate for a particular site.

The procedure is presented in six steps in outline form in Figure 10. Steps (1): Perform Coarse Demand/Capacity Analysis, (3): Assess Storage Capabilities for Metering Options, (4): Assess Diversion Potential for Metering Options, and (5): Estimate Travel Time Impacts for Each Feasible Option are described in further detail here. Step (2): Assess Capacity Improvement Options is beyond the scope of these guidelines, but has been included in the procedure to insure that these options are examined as an alternative or in conjunction with metering options. Step (6) is carried out using the results of Step (5), cost data and other factors peculiar to each site. The application of this procedure in any actual situation will entail a considerable amount of feedback to previous steps.

For the important and more specific situation in which the bottleneck conditions are related to traffic coming from a freeway-to-freeway interchange, as depicted in Figure 11, a more detailed version of this procedure is depicted in flow chart form in Figure 12. Referring to Figure 12, possible actions are:

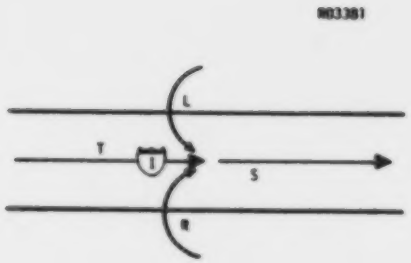

Figure 11. Analysis of Bottlenecks Downstream of an Interchange

(a) Do nothing — The greater the congestion, the greater are the potential benefits of design and/or control solutions. The use of deterministic queueing analysis can be helpful in estimating potential benefits. If some improvement is desired, consider

(b) Increase capacity at bottleneck(s) — Deterministic queueing analysis can be used to estimate capacity increase requirements. Investigate new bottlenecks developing downstream if capacity at upstream bottleneck(s) are increased. If design improvements are not desired or if design improvements are not sufficient, consider

(c) Ramp control between the interchange and bottleneck(s) — A quick check to see if congestion can be eliminated is to use the equation

$$I_T + I_R + I_L + \sum_{i=1}^{n} M_i > C_B$$

where

I_T = demand on through roadway
I_R = demand on right turn connector
I_L = demand on left turn connector
M_i = minimum metering rate for ramp i (n on ramps between interchange and bottleneck)
C_B = capacity of bottleneck

If inequality is not true, then ramp control is adequate to eliminate congestion. If inequality is true, then ramp control is inadequate to eliminate congestion and three alternatives are possible: reconsider increasing bottleneck capacity, accept freeway congestion and take no further action, or consider additional action(s) upstream.

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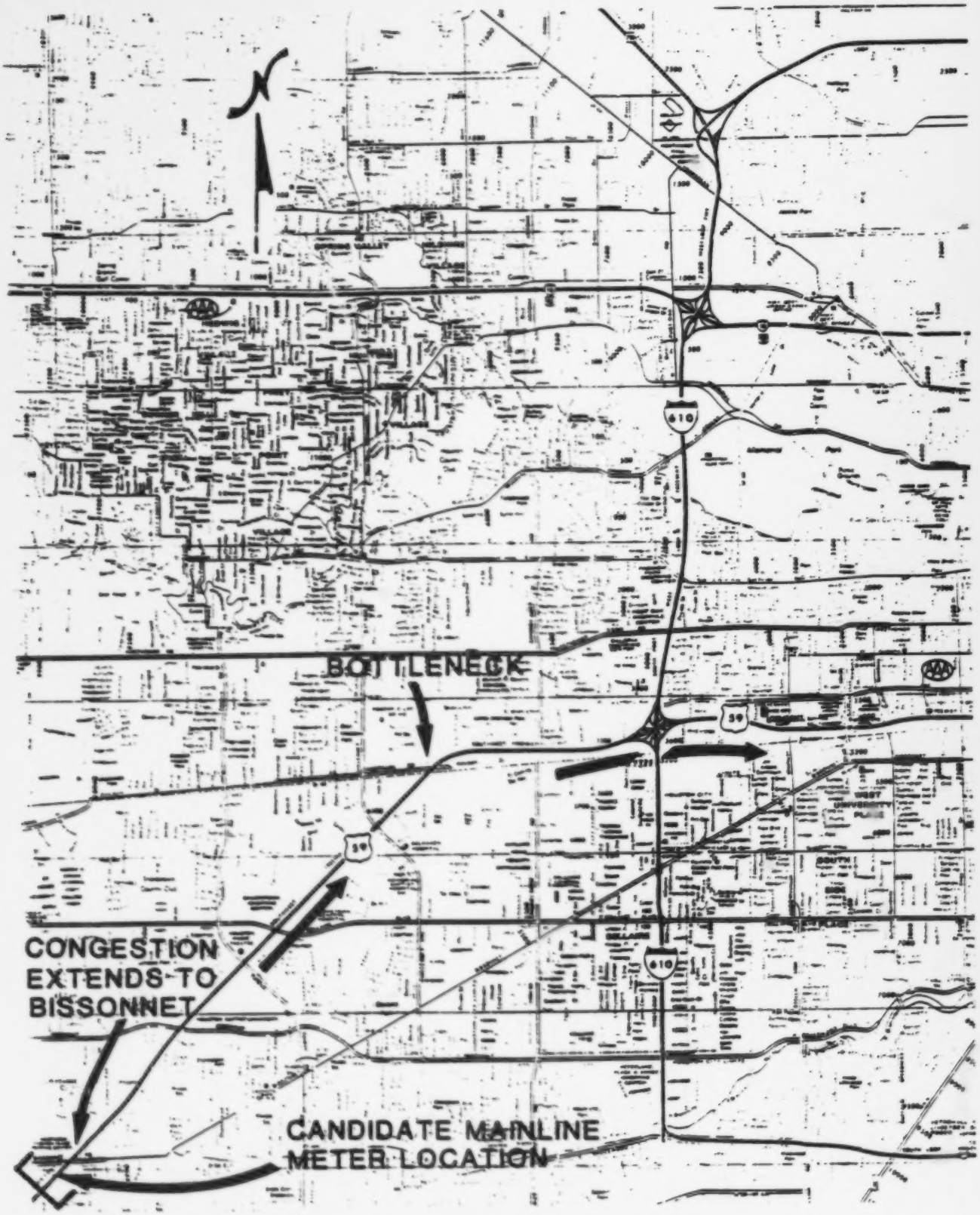

Figure 9. Route 59 (Southwest Freeway) in Houston

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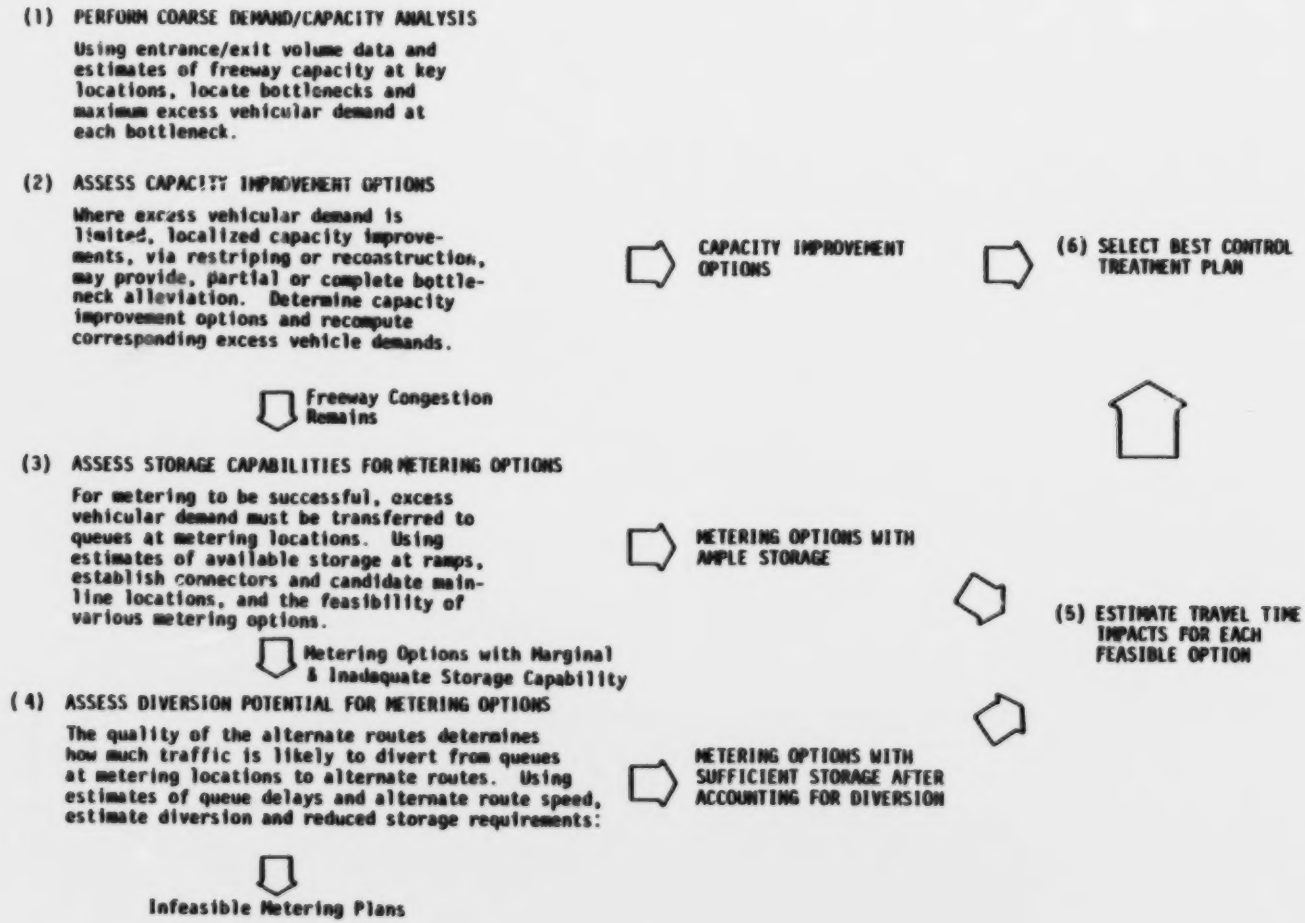
(1) PERFORM COARSE DEMAND/CAPACITY ANALYSIS
Using entrance/exit volume data and estimates of freeway capacity at key locations, locate bottlenecks and maximum excess vehicular demand at each bottleneck.
(2) ASSESS CAPACITY IMPROVEMENT OPTIONS
Where excess vehicular demand is limited, localized capacity improvements, via restriping or reconstruction, may provide, partial or complete bottleneck alleviation. Determine capacity improvement options and recompute corresponding excess vehicle demands.
Freeway Congestion Remains
(3) ASSESS STORAGE CAPABILITIES FOR METERING OPTIONS
For metering to be successful, excess vehicular demand must be transferred to queues at metering locations. Using estimates of available storage at ramps, establish connectors and candidate mainline locations, and the feasibility of various metering options.
Metering Options with Marginal & Inadequate Storage Capability
(4) ASSESS DIVERSION POTENTIAL FOR METERING OPTIONS
The quality of the alternate routes determines how much traffic is likely to divert from queues at metering locations to alternate routes. Using estimates of queue delays and alternate route speed, estimate diversion and reduced storage requirements:
Infeasible Metering Plans
CAPACITY IMPROVEMENT OPTIONS
METERING OPTIONS WITH AMPLE STORAGE
METERING OPTIONS WITH SUFFICIENT STORAGE AFTER ACCOUNTING FOR DIVERSION
(5) ESTIMATE TRAVEL TIME IMPACTS FOR EACH FEASIBLE OPTION
(6) SELECT BEST CONTROL TREATMENT PLAN

Figure 10. Procedure for Assessing Techniques for Bottleneck Alleviation

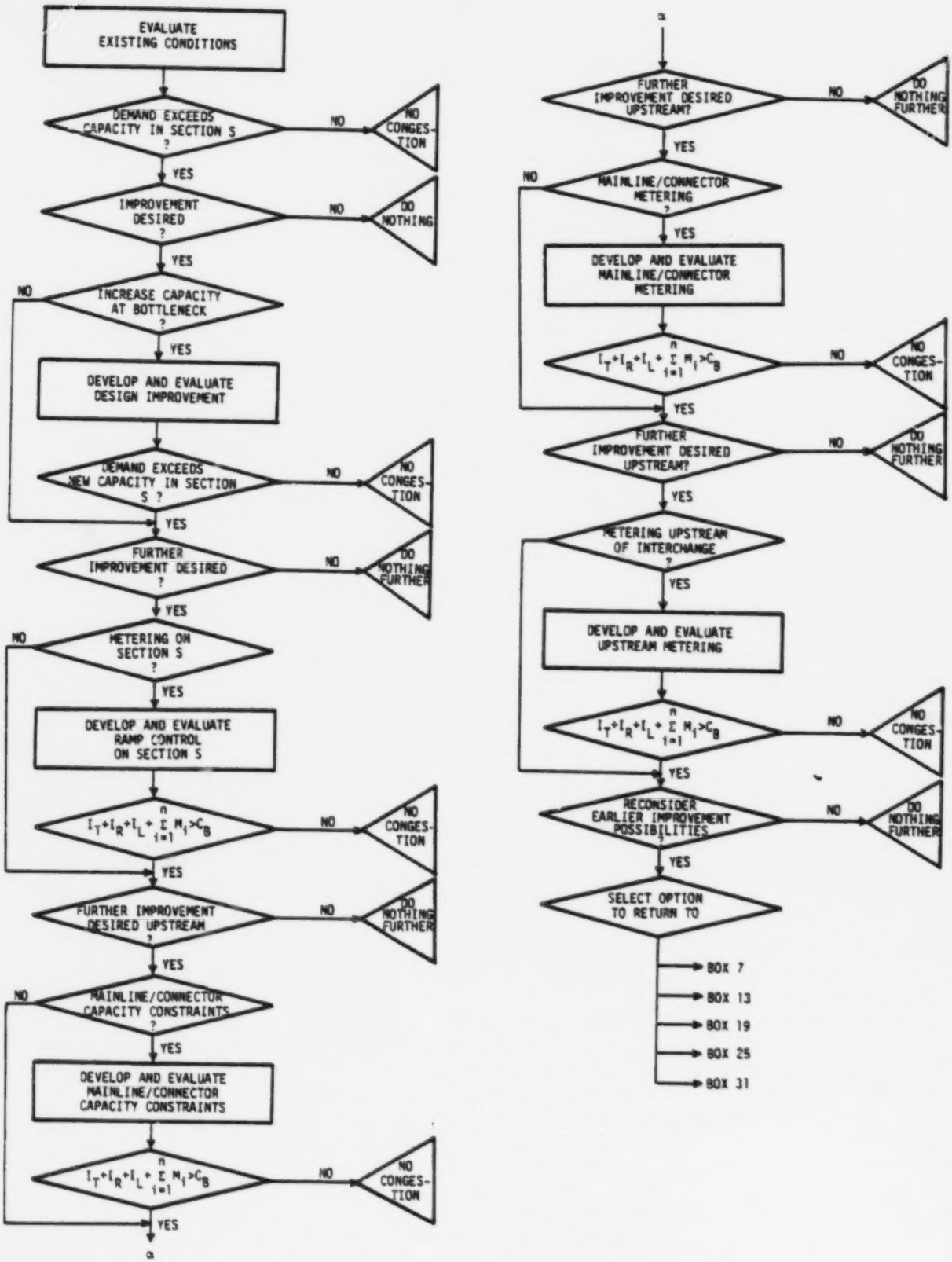

Figure 12. Detailed Procedure for Assessing Techniques for Bottleneck Alleviation

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(d) Introduce capacity constraints on the main roadway and/or connectors within the interchange. This in essence meters the input to the overloaded bottleneck. Normally this type of action is a permanent one and is in effect 24 hours per day whether desired or not.

(e) Introduce mainline and/or connector(s) metering. The two key elements are to warn motorists in advance of mainline and/or connector(s) metering and to ensure that queues do not extend upstream far enough to inhibit vehicles who are not destined for the bottleneck and beyond. Deterministic queueing analysis can be used to estimate the length of the queue. If mainline and/or connector(s) metering is not desired but yet the elimination of congestion is desired, then consider

(f) Ramp control on one or more of the upstream freeways (T, R, and/or L). The disadvantage of this alternative is that some traffic will be metered which is not destined for the bottleneck and beyond (hence causing an unnecessary delay without benefit of assisting bottleneck conditions).

To illustrate the steps of the procedure of Figure 10, we will treat a realistic problem, Route 94 (westbound) in the San Diego area. The network representation of this segment is presented in Figure 13. There are 15 on ramps, 4 entrance connectors, 11 off ramps, and 4 exit connectors within this segment. From the application of the general screening guidelines, as discussed in Section 2.2.3, it was determined that ramp metering and/or connector metering was necessary to alleviate the moderate bottleneck near the western end of the freeway segment and that connector metering was likely to be appropriate to alleviate the slight bottleneck near the eastern end.

Step (1): Perform Coarse Demand/Capacity Analysis

Entrance/exit demand volume data can be used to compute projected freeway demand volumes. These projections and estimates of freeway capacity are then used to locate bottlenecks (locations where demand exceeds capacity) and to determine the amount of vehicle storage on the freeway. It is recommended that these computations be performed using two or three time slices which cover the period of congestion buildup, the period of maximum congestion, and the period over which congestion dissipates.*

*The method presented here can be regarded as a simplification of the more accurate, FREQ method [ORTH73, JOVA78].

Entrance/exit demand data for three 30-minute time slices are presented in Table 5. (Many operational agencies use 15-minute time slices). Results of the demand/capacity analysis are also recorded there. For each time slice, freeway volumes are determined by adding entrance demand volumes and subtracting exit volumes, starting at the upstream end of the segment (top of the table). Where the computed freeway volume exceeds capacity (indicated by *), the freeway volume is reduced to capacity and the excess number of vehicles is recorded. For a 30-minute time slice, this excess is one-half the excess volume. This adjusted freeway volume is then used in subsequent computations. In the first time slice, two bottlenecks are located by this procedure. In the second time slice, computations proceed in the same manner, except that vehicles stored in Time Slice 1 represent additional demand at that location. For example, at Location 26, the 143 vehicles stored in Time Slice 1 represent an additional demand volume of 286 vehicles per hour. Three bottlenecks are identified in Time Slice 2 (which has peak demands). Similar computations for Time Slice 3 indicate that freeway congestion is gone by the end of this 30-minute interval.

It should be noted that no adjustments to exit volumes downstream of a bottleneck have been made. This is equivalent to making the conservative assumption that all vehicles stored on the freeway are destined for the downstream end of the freeway segment. A more refined (and computationally more complex) analysis could be undertaken using demand volumes in the form of origin-destination data. See Section 4 for a discussion of relevant procedures.

Step (3): Assess Storage Capabilities for Metering Options

Assuming no diversion, on ramp, connector and mainline metering locations upstream of bottlenecks must store the excess vehicle demands in order to remove congestion from the freeway. The ability of several metering options to provide the needed storage can be assessed once estimates of the available storage at each location are determined. Generally, the order of preference for metering options is:

(1) On-ramp metering only
(2) Connector metering only
(3) On-ramp and connector metering
(4) Mainline metering only
(5) On-ramp and mainline metering
(6) Connector and mainline metering
(7) On-ramp, connector and mainline metering

Options (2), (4) and (6) will be viable only in very unusual circumstances.

In the example application, only the first three options are considered. In Table 6, storage capabilities for metering locations are indicated. For those locations with light

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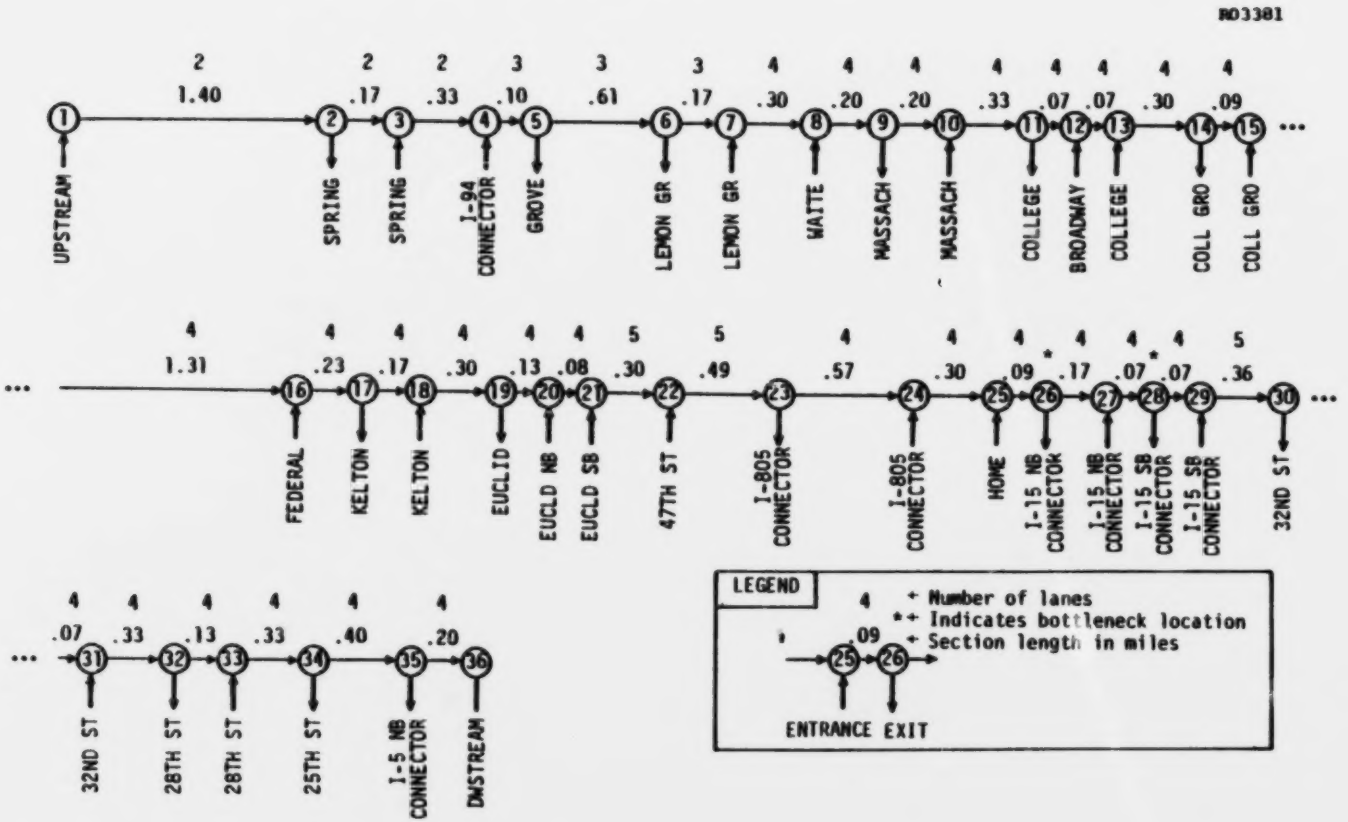

Figure 13. Network Representation of Route 94, Westbound Site in San Diego

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Table 5. Demand/Capacity Analysis

	LOCATION	ENTRANCE	EXIT	FREEWAY CAPACITY (APPROACHING LOCATION) (VEH/HR)	TIME SLICE 1 ENTRANCE/EXIT VOLUME (VEH/HR)	TIME SLICE 1 DOWN-STREAM FREEWAY VOLUME (VEH/HR)	TIME SLICE 1 NUMBER* STORED VEHICLES	TIME SLICE 2 ENTRANCE/EXIT VOLUME (VEH/HR)	TIME SLICE 2 DOWN-STREAM FREEWAY VOLUME (VEH/HR)	TIME SLICE 2 NUMBER** STORED VEHICLES	TIME SLICE 3 ENTRANCE/EXIT VOLUME (VEH/HR)	TIME SLICE 3 DOWN-STREAM FREEWAY VOLUME (VEH/HR)	TIME SLICE 3 NUMBER** STORED VEHICLES
1	UPSTREAM	✓		4000	3184	3184		+3680	3680		3243	3243	
2	SPRING		✓	4000	-229	2955		-250	3430		-354	2889	
3	SPRING	✓		4000	+164	3219		+167	3597		+122	3011	
4	I-94 CONNECTOR	✓		4000	+1936	5155		+2266	5863		+1850	4861	
5	GROVE		✓	6000	-166	4989		-312	5551		-354	4507	
6	LEMON GROVE		✓	6000	-62	4927		-125	5426		-250	4257	
7	LEMON GROVE	✓		6000	+768	5695		+978	6404		+749	5006	
8	WAITE	✓		8000	+521	6216		+500	6904		+457	5463	
9	MASSACHUSETTS		✓	8000	-104	6112		-208	6696		-291	5172	
10	MASSACHUSETTS	✓		8000	+456	6568		+521	7217		+353	5525	
11	COLLEGE		✓	8000	-208	6360		-374	6843		-416	5109	
12	BROADWAY	✓		8000	+250	6610		+209	7052		+230	5339	
13	COLLEGE	✓		8000	+390	7000		+456	7508		+333	5672	
14	COLLEGE GROVE		✓	8000	-104	6896		-167	7341		-145	5527	
15	COLLEGE GROVE	✓		8000	+105	7001		+165	7506		+82	5609	
16	FEDERAL	✓		8000	+706	7761		+790	8000*		+644	6549	
17	KELTON		✓	8000	-249	7512		-478	7522	148	-334	6215	0
18	KELTON	✓		8000	+256	7768		+249	7771		+208	6423	
19	EUCLID		✓	8000	-187	7581		-208	7563		-229	6194	
20	EUCLID NB	✓		8000	+374	7955		+312	7875		+310	6504	
21	EUCLID SB	✓		8000	+518	8473		+667	8542		+645	7149	
22	47th ST	✓		10000	+168	8641		+209	8751		+166	7315	
23	I-805 CONNECTOR		✓	10000	-2663	5978		-3099	5652		-2351	4964	
24	I-805 CONNECTOR	✓		8000	+1560	7538		+1458	7110		+1311	6275	
25	HOME	✓		8000	+748	8000*		+893	8000*		+810	7375	
26	I-15 NB CONNECTOR		✓	8000	-62	7938	143	-41	7959	145	-41	7334	0
27	I-15 NB CONNECTOR	✓		8000	+105	8000*		+146	8000*		+147	7629	
28	I-15 SB CONNECTOR		✓	8000	-978	7022	22	-790	7210	74	-478	7151	0
29	I-15 SB CONNECTOR	✓		8000	+895	7917		+874	8084		+875	8026	
30	32nd ST		✓	10000	-437	7480		-563	7521		-416	7610	
31	32nd ST	✓		8000	+41	7521		+81	7602		+104	7714	
32	28th ST		✓	8000	-415	7106		-375	7227		-290	7424	
33	28th ST	✓		8000	+44	7150		+63	7290		+62	7486	
34	25th ST		✓	8000	-645	6505		-623	6667		-522	6964	
35	I-5 NB CONNECTOR		✓	8000									

*Section at capacity

**Since each time slice is of thirty minutes duration, and volumes are hourly values, the change in the number of stored vehicles is 1/2 (demand-capacity).

Table 6. Assessment of Storage Capabilities for Metering Options

ENTRANCE LOCATION	ON RAMP	CONNECTOR	STORAGE CAPACITY (VEHICLES)	RAMP QUEUE (VEHICLES)					
				RAMP METERING ONLY		RAMP METERING ONLY		RAMP AND CONNECTOR METERING	
				TIME SLICE		TIME SLICE		TIME SLICE	
				1	2	1	2	1	2
3 SPRING	✓		36						
4 I-94		✓	73				73		33
7 LEMON GROVE	✓		9	2	9				9
8 WAITE	✓		16	16	16				16
10 MASSACHUSETTS	✓		20	20	20				20
12 BROADWAY	✓		19	5					
13 COLLEGE	✓		20	20	20				20
15 COLLEGE GROVE	✓		24						
16 FEDERAL	✓		32	32	32				32
18 KELTON	✓		48	8	13				5
20 EUCLID NB	✓		16	16	16				16
21 EUCLID SB	✓		14	14	14				14
22 47th ST	✓		8						
24 I-805		✓	170			165	170	133	170
25 HOME	✓		32	32	32			32	32
27 I-15 NB		✓	12						
29 I-15 SB		✓	36						
31 32nd ST	✓		14						
33 28th ST	✓		15						
TOTAL				165	172*	165	243*	165	367

*Available storage is insufficient.

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demand, application of a minimum metering rate of 240 veh/hr will generate little or no queueing. The amount of storage allocated to each location in order to handle the excess vehicle demands generated in Table 6 are also shown there for the three options. The procedure adopted in doing this is to assign storage to the nearest locations upstream of each bottleneck. Generally, one must start at the furthest downstream bottleneck. The limitation on storage due to limited demand as noted above has also been accounted for.

Application of this procedure indicates that the ramp metering only and connector metering only options do not provide adequate storage. The ramp and connector metering option does, however, provide adequate storage.

It should be noted that this method of assessing storage capability assumes that all vehicles stored at metering locations are destined for the bottleneck(s). Where metering locations are near the bottleneck, this represents an excellent approximation, since there are no or at most a few exit locations in the intervening freeway segment to which these vehicles might be destined. Where metering locations are a great distance upstream of the bottleneck, or where there are one or more high volume exits in the intervening segment, a substantial fraction of vehicles stored at these metering locations have destinations upstream of the bottleneck. Therefore, it is necessary to store substantially more vehicles at these locations so that the fraction of those stored which are actually destined for the bottleneck is sufficient to handle the excess demand at the bottleneck.

In the example application, storage in Time Slice 1 is at metering locations immediately upstream of the bottlenecks, so that the indicated storage requirements are quite accurate. In Time Slice 2, metering extends a great distance upstream of the bottleneck(s); further, the I-805 exit connectors carry very high volumes and are located upstream of the furthest downstream bottleneck. As a result, additional storage (or diversion) at metering locations is necessary. Additional storage (or diversion) at the Route 94 connector and the seven ramps between the Route 94 and I-805 interchanges will certainly be necessary.

More refined (and computationally more complex) procedures, using origin-destination data, can properly account for the destinations of stored vehicles. See Section 4 for relevant procedures. Another option is to use available computer models, e.g., FREQ [ORTH73, JOVA78].

Step (4): Assess Diversion Potential for Metering Options

The quality of the alternate route determines the attractiveness of diversion to drivers who are subject to delays at metering locations. A high speed alternate route would allow some drivers to divert from a queue at a metering location to the alternate and thereby achieve a travel time savings. Specifically, such savings occur where the trip is short enough that the travel time on the street is less than the travel time to the freeway through the ramp queue, on the freeway, and finally away from the freeway.

Where the alternate is poor, only drivers taking very short trips will find the alternate attractive. A conservative approach in this instance is to assume that no vehicles will divert. In this instance, design options which were determined in the previous step to be incapable of providing adequate storage can be expected to be incapable of simultaneously relieving the congestion on the freeway and meeting queue storage limitations.

In order to estimate the diversion potential where the quality of the alternate is at least good, each candidate metering location is examined individually. First, the time required by a vehicle approaching the end of the queue to travel through that queue is estimated through the simple relationship

$$\text{queue travel time} = \frac{\text{queue length}}{\text{metering rate}}$$

Of course, the metering rate has not been determined, but, due to limited storage, it turns out that metering rates are close to demand volume, so that one may use the approximation

$$\text{queue travel time} = \frac{\text{queue length}}{\text{demand volume}}$$

Next, one ascertains the maximum trip length for which travel on the alternate is as fast as travel through the queue and then on the freeway. Letting ℓ denote this trip length, S_f denote the freeway speed, and S_a, the alternate route speed, this trip length ℓ must be such that

$$\frac{\ell}{S_f} + \text{queue travel time} = \frac{\ell}{S_a}$$

Hence

$$\ell = \text{queue travel time} \Big/ \left(\frac{1}{S_a} - \frac{1}{S_f}\right)$$

Next, one estimates the fraction of the drivers having trip lengths less than this value. This can be done with a trip length distribution of the sort illustrated in Figure 14. (This trip length distribution is not based upon any data; it is presented purely for the purpose of illustrating the procedures. In making use of the procedures

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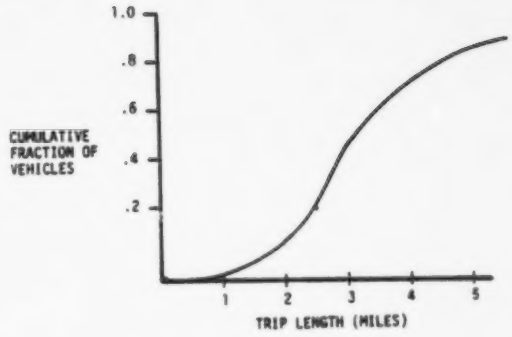

Figure 14. Hypothetical Trip Length Distribution

presented here, one would have to identify an appropriate trip length distribution, or, as we illustrate shortly, use a simple linear distribution function with a single characteristic parameter.) For example, if the "critical" trip length were determined to be 2.5 miles, one finds from Figure 14 that .2 of the vehicles have trip lengths sufficiently short that the alternate route is faster.

The effective storage (i.e., the number of vehicles stored plus the number of vehicles diverted) at a metering location is increased by diversion, according to the relation

$$\text{effective storage} = \frac{\text{final queue}}{1 - \text{fraction diverted}}$$

The final step in this assessment is to use these values of effective storage to reestablish storage requirements at metering locations.

Adopting some notation for the quantities involved here, and further, assuming that the trip length distribution is uniform, results in some simple, useful relationships. Let

- q = final queue after diversion (number of vehicles)
- d = demand (vehicles/hour)
- s = effective storage (queued plus diverted vehicles)
- f = fraction diverted
- p = trip length distribution parameter (1/mile); the fraction p of the vehicles have trips between zero and one mile, between one mile and two miles, etc. (This has to be determined independently. Note that the corresponding mean trip length is 1/2p miles.)

$$\tau = \frac{1}{S_a} - \frac{1}{S_f} \quad \text{(hours/mile)}$$

Using this additional notation, the critical trip length, ℓ, is expressible as

$$\ell = q/d$$

The fraction diverted, being the fraction of vehicles with trip lengths less than ℓ, is

$$f = p\ell$$

Then, the effective storage is expressed as

$$s = \frac{s}{1 - pq/d\tau}$$

and the number diverted is s-q. In using these relationships, one uses the maximum physical storage to specify q, from which the effective storage and number of diverted vehicles are then computed. At the furthest upstream location at which metering is required, the remaining storage requirement is used to specify the effective storage, from which the actual queue is then computed from

$$q = \frac{s}{1 + ps/d\tau}$$

For the example, assume that the freeway speed is 55 mph and the alternate route speed is 20 mph; thus, τ = .0318 hrs/mile. Further, assume that the cumulative trip length distribution is 20 percent of the vehicles per mile, i.e., 20 percent of the vehicles travel a mile or less, 20 percent travel between one and two miles, etc; thus p = .2. Results of computations for this example (ramp and connector metering option) are presented in Table 7. For the first time slice, a total of 52 vehicles are expected to divert. This results in a reduction of the required queue storage, indicated for Location 24, I-805 connector, to 81 vehicles. For the second time slice, the total queue storage and diversion (i.e., effective storage) requirement of 367 vehicles is met by actually storing 250 vehicles at metering location and by diverting 117 vehicles.

Step (5): Estimate Travel Time Impacts for Each Feasible Option

In the absence of metering, delay to motorists is directly related to the excess vehicle demand at bottlenecks. A simple technique for estimating this delay is

delay = vehicles stored x time stored

Under a metering system, delay at metering locations is determined in the same fashion. However, it is also necessary to account for the additional travel time associated with vehicles which use alternate routes. This time can be estimated for each metering location through the relationship

$$\text{alternate route penalty} = \frac{(\text{queue length}) \times (\text{number of diverted vehicles})}{2 \times \text{demand}}$$

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Table 7. Assessment of Diversion Potential for Combined Ramp and Connector Metering

ENTRANCE LOCATION	STORAGE CAPABILITY (VEHICLES)	TIME SLICE 1					TIME SLICE 2				
		DEMAND VOLUME (VEH/HR)	EFFECTIVE STORAGE (VEH)	QUEUE (VEH)	NUMBER DIVERTED (VEH)	ALTERNATE ROUTE PENALTY (VEH-HRS)	DEMAND VOLUME (VEH/HR)	EFFECTIVE STORAGE (VEH)	QUEUE (VEH)	NUMBER DIVERTED (VEH)	ALTERNATE ROUTE PENALTY (VEH-HRS)
3 SPRING	36	164					167				
4 I-94 CONNECTOR	73	1936					2266	21	20	1	.00
7 LEMON GROVE	9	768					978	10	9	1	.01
8 WAITE	16	521					500	20	16	4	.06
10 MASSACHUSETTS	20	456					521	26	20	6	.01
12 BROADWAY		250					209				
13 COLLEGE	20	390					456	28	20	8	.17
15 COLLEGE GROVE		105					165				
16 FEDERAL	32	706					790	43	32	11	.22
18 KELTON	48	256					249				
20 EUCLID NB	16	374					312				
21 EUCLID SB	14	518					667				
22 47th ST		168					209				
24 I-805 CONNECTOR	170	1560	121	81	40	1.04	1458	178	170	77	2.67
25 HOME	32	748	44	32	12	.26	893	41	32	9	.16
29 I-15 NB CONNECTOR		105					146				
29 I-15 SB CONNECTOR	36	895					874				
31 32nd ST		41					81				
33 28th ST		44					63				
TOTAL			165	113	52	1.30		371	250	117	3.30

Benefits of the metering system are then determined as the difference between the delay incurred without metering and the sum of metering delays and alternate route penalty under metering.

Results of computations for the example are presented in Table 7. From Table 5, the number of stored vehicles are used to determine that the delay in the absence of metering is 266 vehicle-hours. From Table 7, the number of stored vehicles indicates queueing delay of 181.5 vehicle-hours. The alternate route penalty is computed to be 4.6 vehicle-hours for a total of 186 vehicle-hours of delay for the ramp and connector metering system, a savings of 80 vehicle-hours.

Queueing delay estimated by the procedures presented here is related to "localized" delay only. That is, it does not account for delays imposed on vehicles caught in the queue but not destined for the bottleneck. Where traffic demand is moderate to heavy, removal of congestion from the freeway has substantial additional benefits related to elimination of these other delays. These are, however, difficult to estimate by simple means. In these circumstances, it is necessary to use a dynamic simulation model, such as FREQ [JOVA78], FREFLO [PAYN78], or INTRAS [WICK77] to generate estimates of travel time savings. Were such methods to be applied to the example presented here, it is likely that further significant benefits of the metering plan would be predicted.

2.4 Other Considerations

The preceding subsections have addressed various technical issues pertinent to the implementation of mainline and connector metering. As these forms of metering are not in general use throughout the nation, the issue of acceptance on the part of the general public and public officials must also be addressed.

Connector metering has been successfully implemented in the San Diego and Minneapolis areas. The information contained in Section 3 and Appendix A of this report pertaining to these installations should serve as useful documentation when a proposal for connector metering is presented.

Experience with connector metering has established that such metering can be implemented much as is on-ramp metering, except that driver expectations of high speeds on freeway-to-freeway connectors require advance warning signs, and consideration must be given to the queue which can be expected to develop. Appendix A documents successful implementations of advanced warning signs and positive operational experience with respect to natural concerns about safety. To deal with the connector queue, restriping reconstruction and operational procedures may be used to provide more storage. Traffic responsive schemes which measure queue growth and open up the connector metering rate if necessary (i.e., queue override technique) may also be necessary. It is noteworthy that in existing implementations, connector metering was implemented at the same time as ramp metering so that the use of connector metering was approached as a logical component of a system metering scheme.

Nonetheless, the predisposition of the public and/or public officials with respect to this new form of metering should be assessed and properly accounted for in presenting plans that include connector metering.

The situation with mainline metering is more difficult. There are existing implementations which might be regarded as mainline metering. One of these is the metering of the San Francisco/Oakland Bay Bridge. A second is the control of access to tunnels which has been successfully operated by the Port of New York Authority for some twenty years. A third instance is the metering of the Route 94 WB traffic lanes approaching the Route 125/Route 94 interchange in the San Diego area. A fourth instance is the manual metering of the merge area at the intersection of the Geroge Washington and Spout Run Parkways in the Washington, D.C. area. Documentation of these installations is provided in Section 3 of this report; further detailed documentation of the San Diego site is provided in Appendix A. None of these installations, however, is specifically in the form of metering on a straight, unobstructed freeway section.

Mainline metering is generally regarded as a radically different form of metering, as it imposes control on the freeway itself. In some states, there are existing legal restrictions prohibiting control of this sort. In any case, the affected public will certainly regard such metering very differently than it does on-ramp or even connector metering.

This study has provided evidence that mainline metering may provide significant travel time benefits in certain circumstances. Where freeway congestion cannot be eliminated by other, generally accepted means, mainline metering with appropriate advance warning signs might be considered as a means to better manage the on freeway congestion. It is to be emphasized that any such implementation should not itself introduce congestion on the freeway, but either should be placed where congestion already exists or where it would move the congestion to a location with more storage capacity.

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3.0 SITE VISITS

In order to support the objectives of this study, sites in six metropolitan areas of the United States were visited, as illustrated in Figure 15.

The operational experience of freeway operations personnel makes them particularly valuable sources of specific data pertinent to candidate sites, and for more qualitative information pertaining to traffic scenarios, expected impacts of application of control devices, and expected operational problems and potential remedies.

The specific objectives of the site visits were to:

(1) Obtain geometric and traffic demand data; and

(2) Obtain the benefit of the operational experience of freeway operational personnel in identifying situations (geometrics, traffic demand) in which the freeway mainline and freeway connector control might provide benefits, in understanding the traffic flow mechanisms which contribute to bottlenecks, in assessing candidate traffic signal control mechanisms, and in addressing expected operational problems.

3.1 Site Selection

Eight agencies in seven metropolitan areas were contacted by phone to inform them of project objectives and to solicit their participation in the site visits. Letters were subsequently sent to each agency to formally request a written indication of interest in participation and to request certain site-specific descriptions. All eight agencies responded positively.

A summary of characteristics for a total of 23 candidate sites provided by these agencies is presented in Table 8.

In selecting sites to be visited, the following criteria were applied:

(1) Sites must exhibit recurrent congestion; congestion must be related to major merges, as of two freeways, or a freeway and a connector (ramp merging is excluded).

(2) The traffic situation (geometrics and traffic demand) must be such that on-freeway control is reasonably expected to provide a benefit.

(3) Geometric and traffic demand data must be available.

(4) The set of sites should span a wide range of different bottleneck and connector situations.

Of course, current implementations were preferred, as they provide directly relevant operational experience.

As can be seen from the summary of site characteristics presented in Table 8, there were many more candidate freeway-to-freeway connector metering sites than mainline metering sites. It was therefore highly desirable to visit the three areas where mainline metering exists or had been considered. These areas include:

- San Francisco area, with the San Francisco/Oakland Bay Bridge metering implementation (Site SF-1)
- Capitol areas, with the manual metering of the Spout Run/George Washington Parkway intersection (Site CA-1), and the candidate mainline metering of the Shirley Highway (Site CA-4)
- Houston area, with the existing conceptual plan for metering the Southwest Freeway (Site HO-2).

With the wealth of freeway-to-freeway connector sites available, it was sensible to focus on areas with existing implementations. These areas are:

- Minneapolis, with four connector metering sites implemented, and
- San Diego, with three connector metering sites implemented.

These implementations are discussed in detail in Appendix A.

The set of sites selected for visits included all of these sites. In addition, additional sites were visited where this was particularly convenient. Specifically, the candidate mainline site in San Francisco (SF-2) was included, particularly since the number of mainline sites is limited. For similar reasons, the Houston area connector metering site (HO-3) was also visited. Finally, the two Los Angeles sites (LA-1 and LA-2) were included since relatively little extra effort was entailed. The set of sites visited are noted in Table 8.

3.2 Findings from the Site Visits

In this section, we present discussions pertaining to the 14 sites in six metropolitan areas visited. In each discussion, a map of the area containing sites and associated freeway segments are provided. The general traffic situation is reviewed and the status of implementations or plans is identified.

In order to assure that useful data were gathered for each site, a data item checklist was provided in advance of each visit to each agency, so that most data had been accumulated by the agency prior to the visit. At the time of the visit, the data were reviewed for

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Figure 15. Six Metropolitan Areas Visited

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Table 8. Summary of Candidate Site Characteristics

Agency	Site Designator	Location	Type of Metering	Status	Visited
District 11 California	SD-1	94/15 South San Diego	two connectors	implemented 1971	X
	SD-2	94/805 South San Diego	one connector	implemented 1978	X
	SD-3	94/125 South San Diego	two connectors	implemented 1978	X
District 7 California DOT	LA-1	405/11 South Los Angeles	two connectors	design plans	X
	LA-2	405/10 West Los Angeles	mainline with connector (optional)	no plans	X
District 4 California DOT	SF-1	San Francisco/ Oakland Bay Bridge	mainline	implemented	X
	SF-2	24/580 Oakland	mainline	no plans	X
	SF-3	101/280 San Jose	two connectors	implemented	
	SF-4	17/280 San Jose	four connectors	partially implemented	X
Minnesota DOT	MN-1	Rte 36/35E North of St. Paul	two connectors	implemented 1971	
	MN-2	Rte 65/94 Minneapolis	two connectors	implemented 1974	X
	MN-3	494/35W Bloomington	four connectors	implemented 1975	X
	MN-4	Rte 13/35W Burnsville	two connectors	implemented 1974	
CAESP Illinois DOT	CH-1	Northwest tollway exit to I-90, Rosemont	mainline	no plans	
	CH-2	I-90, 94/290 downtown Chicago	connector	no plans	
District 12 Texas SDHPT	HO-1	Rte 45/75 north of Houston	mainline	conceptual plan	
	HO-2	Rte 59 at Bissonnet in Houston	mainline	design plans	X
	HO-3	I-610/45 in Houston	two connectors	conceptual plan	
	HO-4	I-610/59 in Houston	two connectors	in planning	X
National Park Service	CA-1	Spout run/ George Washington Parkway	manual mainline	implemented	X
Virginia DH and T	CA-2	I-66/I-395 Merrifield	connector	no plans	
	CA-3	I-95-495/ I-495 Springfield	connector	no plans	
	CA-4	I-395 Alexandria	mainline	no plans	X

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completeness and to assure conformance with the intent of the stated data requirement.

The second important portion of each site visit was a trip to the site to observe traffic conditions. The principal purposes here were to:

(1) Observe the cause or causes of the bottleneck condition,

(2) Observe the operation of the traffic flow in the bottleneck area,

(3) Observe the geometric and traffic conditions influencing the (potential) operation of metering signals - restricted sight distances and high speed approaches, for example, and

(4) Observe the impact of the bottleneck on neighboring sections of the freeway or freeways involved.

The third portion of each site visit was a general discussion with operational personnel to obtain the benefit of their experience as it may relate to connector or mainline metering. Important topics which were discussed included:

(1) Traffic flow mechanisms which contribute to bottlenecks - geometric capacity restrictions, merge inefficiency;

(2) Candidate traffic control mechanisms, including but not necessarily restricted to metering;

(3) Beneficial or intended effects of traffic control - diversion to better utilize corridor capacity, displacement of queues to a location with less adverse operational effects, improved merge area capacity due to regularity induced by metering;

(4) Operational problems - high speed approaches to metering locations, restricted sight distances, spillback of queues to an upstream freeway (especially in connector metering); and

(5) Possible remedies for operational problems - advance warning signs and signals, restriping to improve queue storage or to remove tail of queue out of mainline flow.

The detailed geometric and traffic demand data gathered from five areas were subsequently used to define a set of representative traffic scenarios for use in the analytic study of mainline and connector metering. Details of the geometrics and traffic demands are recorded in Section 6. Results of the analytic examination are recorded in Section 5.

3.2.1 San Diego Area Sites

The three San Diego area connector metering sites (SD-1, SD-2, and SD-3) are all associated with Rte 94 westbound traffic, as previously illustrated in Figure 7. These are existing implementations which are a part of a system metering plan used to control AM peak traffic. Ramp metering is used along Rte 94 starting at locations immediately downstream of the 94/125 connector at the eastern end of this section and continuing at all locations up to the I-5 interchange at the western end. The first installation of metering in this section was on the I-15 southbound to Rte 94 westbound connector in 1971 and was aimed at alleviating a bottleneck in that interchange area. All remaining metering was implemented in 1978.

The Wye interchange of Rte 94 and Rte 125 at the eastern end of this section (Figure 16) is followed by a three-lane section on Rte 94 which had become congested. Metering of the Rte 94 approach has proven to effectively alleviate this congestion.

Traffic demand on Rte 94 is sufficient to create freeway congestion in the absence of metering, but is not greatly in excess of freeway capacity. However, the accumulation of demand and complex of freeway-to-freeway interchanges at the western end of this segment does lead to a situation where substantial congestion would occur in the absence of metering. Much of the demand in this area is introduced via connectors. The implementation of ramp and connector metering in 1978 has proven to be effective in eliminating congestion and, in fact, in successfully absorbing additional demand since that date. Figure 17 presents an aerial view of one of the connectors near the western end of this freeway segment. See Appendix A for additional information.

A substantial amount of additional detail concerning the implementation of metering, with associated signing and operational experience, is available in [CARL80, see also Appendix A].

The westbound Rte 94 freeway segment containing these three interchanges and all the associated metered ramps was used as a basis for one of the five cases investigated in the latter portion of this study.

3.2.2 Los Angeles Sites

The two sites visited in the Los Angeles area (LA-1 and LA-2) are in distinct areas, as illustrated in Figure 18. Ramp metering has been implemented on the associated freeway segments in each case, but neither mainline nor connector metering has in either case.

The LA-1 site is the interchange of Route 11 (Harbor Freeway) and I-405 (San Diego Freeway), where concern is focused on westbound AM traffic on I-405 and the

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Figure 16. Connector Metering at the Interchange of Rte 94 and Rte 125 in San Diego (Site S-3)

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Figure 17. Connector Metering at the Interchange of Rte 15 and Rte 94 in San Diego (Sites 4+5)

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Figure 18. Los Angeles Area Sites

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connectors from Route 11 to westbound I-405. This is a very heavily travelled freeway, for which ramp metering has been implemented since the late 60's. This metering was implemented over a thirteen-mile segment extending from ramps immediately downstream of the Route-11 interchange. Initially, ramp metering was successful in eliminating freeway congestion, but two factors conspired over subsequent years to lead to a return to a congested freeway situation. First, there occurred a substantial diversion of demand to the uncontrolled connectors and mainline at the upstream end of this segment. This effect was countered by increasingly stringent ramp metering and was successful for only a limited time. Second, there occurred a general growth in traffic demand, particularly as reflected in the connector and mainline traffic. The result was a traffic demand which could no longer be effectively controlled by ramp metering alone. Recognizing that the uncontrolled connector demand was a major source of the problem, plans for connector metering were developed in 1973 [EWIN73]. Among the technical issues addressed were provisions for queue storage for the connector traffic and advance warning signs (see Figure 3). While the attendant traffic engineering studies strongly indicated benefits from such metering, local political considerations precluded implementation. At issue there was the perception that connector metering was fundamentally different from ramp metering in that control was imposed on the freeway. Presently, the freeway is typically congested in the vicinity of the interchange and on the immediately downstream segment over a distance of a few miles.

The second site in the Los Angeles area (LA-2) is near the western end of the segment of I-10 (Santa Monica Freeway) stretching from the City of Santa Monica on the west to the Los Angeles Central Business District on the east (Interchange of Rte 11, Harbor Freeway). Ramp metering has been implemented in both directions. Interest here is in the eastbound segment and the AM peak period. This is also a very heavily travelled freeway segment. At the western end, there are three lanes of traffic carried under the I-405 interchange, expanding to five lanes with the merge of connectors, dropping to four lanes after the first downstream off ramp. Beyond that point, the geometry is very complex, involving a two-lane collector-distributor near the eastern end of this segment. The local geometrics in the vicinity of the I-405 interchange, coupled with heavy demand, has led to congestion in this area. This in turn leads to the possibility that mainline and/or connector metering might provide an effective remedy to the localized congestion. A schematic of the geometrics in this area and the candidate location for metering is presented in Figure 19. While Caltrans has not developed any plans relating to these possibilities, discussions with Caltrans personnel did indicate the technical feasibility of such implementation with regard to queue storage and adequate sight distance for necessary advance warning signs.

The eastbound I-10 freeway segment extending from the I-405/I-10 interchange on the west to the Rte 11/I-10 interchange on the east was used as a basis for one of the five cases investigated in the latter portion of this study.

3.2.3 San Francisco Area Sites

Three sites were visited in the San Francisco area. The first of these (SF-1) was the east terminal area of the San Francisco/Oakland Bay Bridge where there is an existing metering system, previously depicted in Figure 1. The second (SF-2) was the Rte 24/I-580 interchange area in Oakland, for which a conceptual plan for mainline metering was considered. The locations of this site is indicated in Figure 20. The third site (SF-4), located in San Jose, was the I-280/Rte 17 interchange and the associated segment of Rte 17. The location of this third site is shown in Figure 21. Connector metering was examined for this site.

Figure 1 presents a detailed diagram of the geometrics of site SF-1. Presently, there are 17 toll booths of which three are reserved for HOV vehicles. (These vehicles do not stop at the toll booths.) There are 15 metering signals (three for HOV vehicles). Immediately thereafter, 1/2 mile downstream, there are five lanes for all vehicle types. The capacity constraint is related to the upgrade on the bridge. Capacity is estimated to be approximately 8800 vehicles.

Peak volumes occur from 0600 to 0900. These volumes typically exceed capacity for the interval 0630-0830, during which metering is employed. HOV vehicles pay no tolls, have three reserved access lanes through the toll booths and through the metering area. They do not stop at either location. Other vehicles stop at one of 14 toll booths and then at one of 12 metering signals 1000' downstream of the toll booths. Downstream of the metering signals, all vehicles merge to five lanes which are available to both HOV and non-HOV vehicles.

Metering is designed to hold traffic volume entering the bridge to a level which does not exceed the capacity constraint associated with the long upgrade. The metering scheme is responsive to the vehicle occupancy measured at the beginning of the upgrade. The total passenger-car-equivalent volume allowed through the metering area is a function of this occupancy. HOV vehicles are not metered, but vehicle type is deduced for these and all non-HOV lanes as the vehicles pass over induction loops in the metering area. For each vehicle type there is an associated pce value (in the range 1 to 5). Metering in the non-HOV lanes realizes the difference in the total pce rate desired and the HOV pce rate. Non-HOV lanes are selected in a fixed pattern

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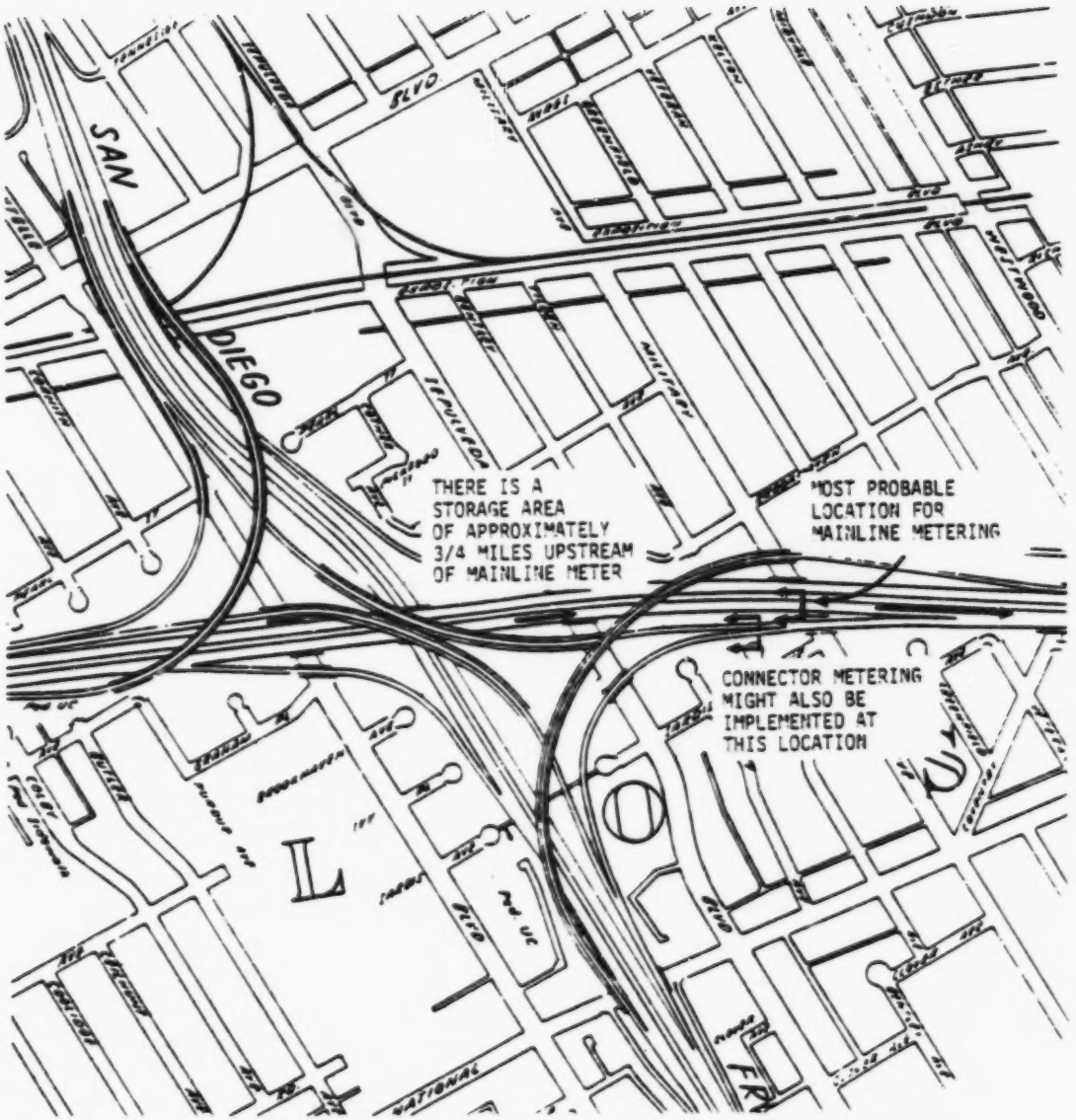

Figure 19. Candidate Mainline Metering at Interchange of San Diego and Santa Monica Freeways in Los Angeles (Site LA-2)

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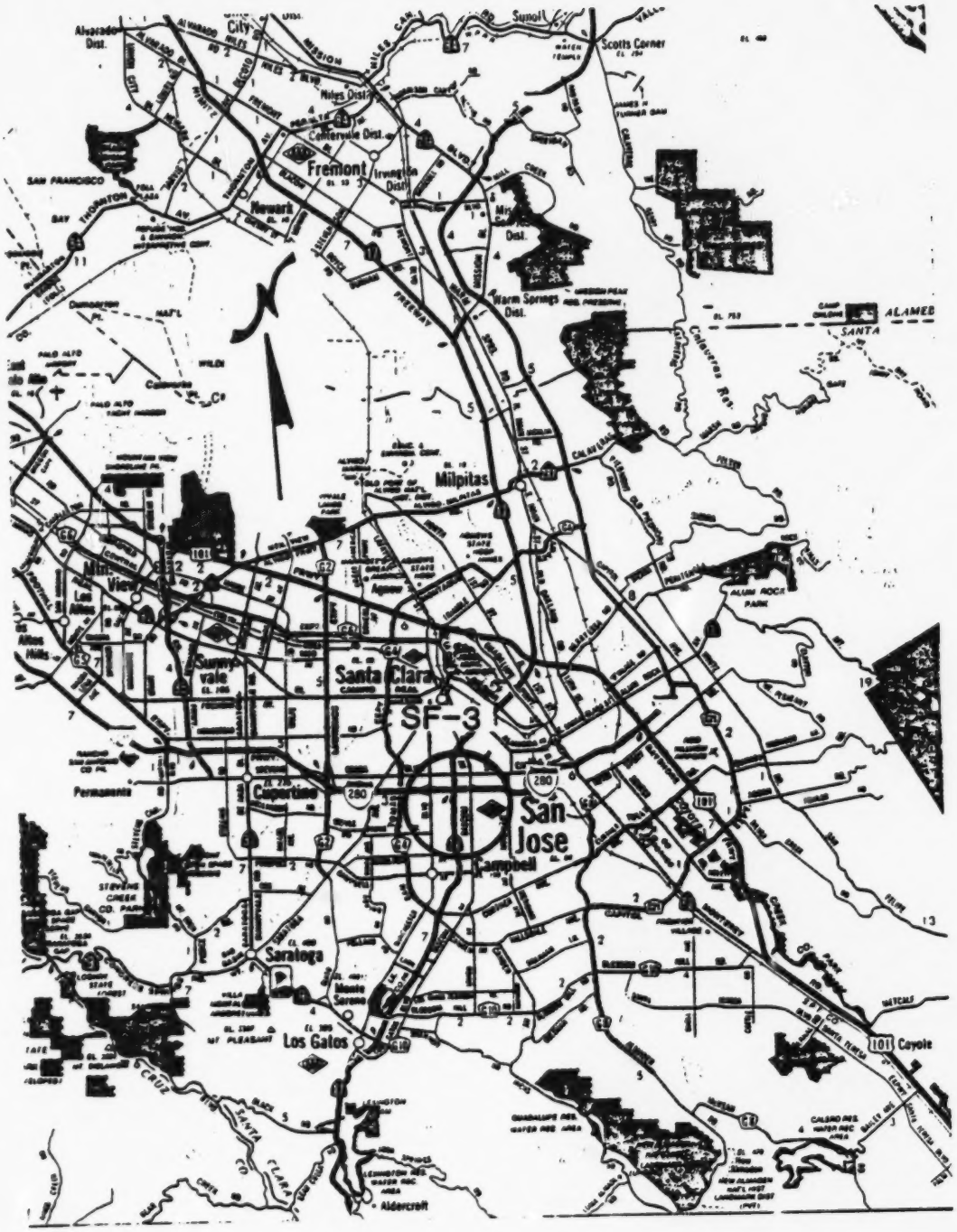

Figure 20. Location of SF-2 Site (Rte 24/I-580 Interchange)

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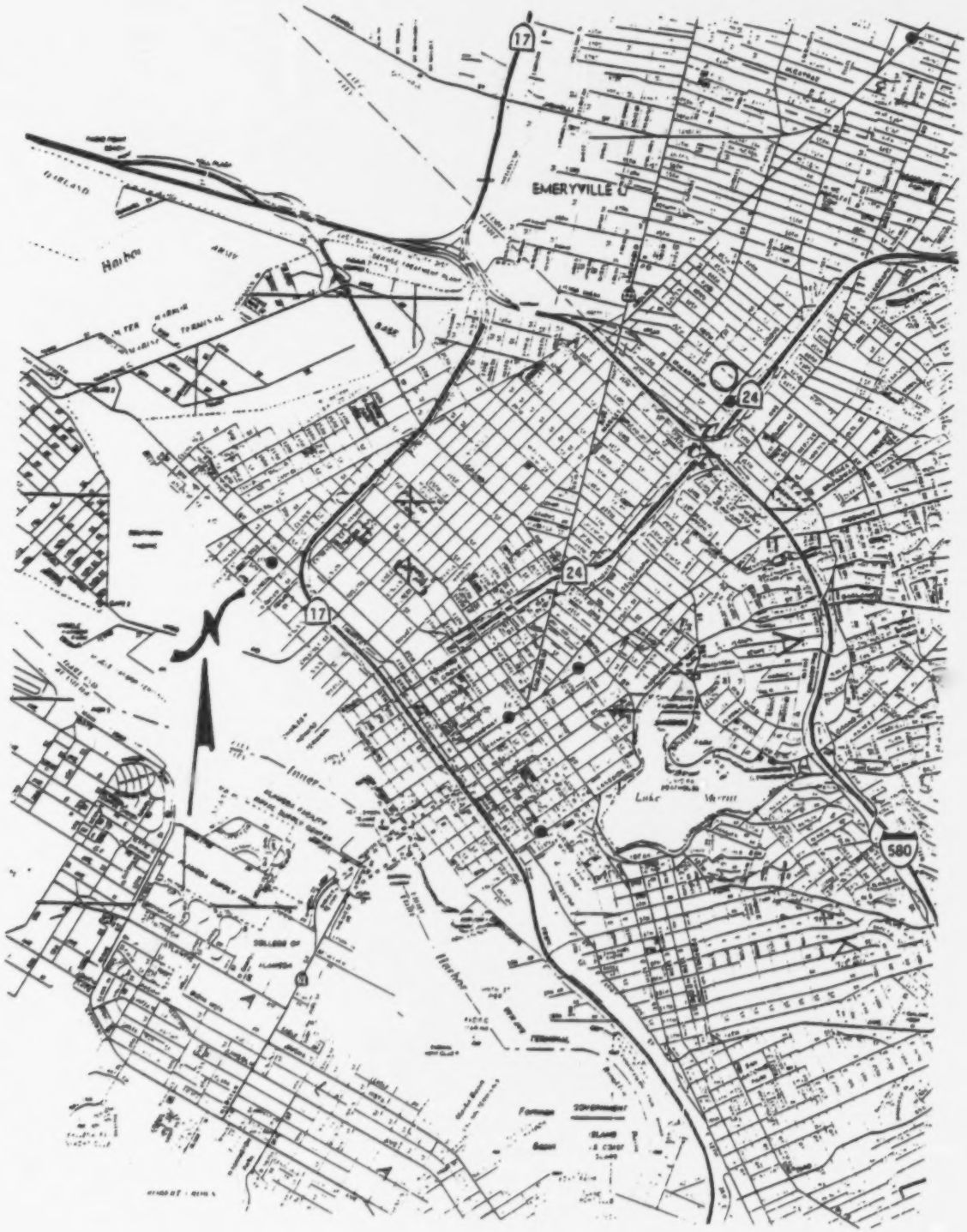

Figure 21. Location of Site SF-4 in San Jose

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for release of vehicles so that adjacent lanes do not receive green indications at the same time.

This metering scheme has been very effective in achieving the stated objective. Queueing of non-HOV vehicles is generally confined to the area between the metering signals and the toll booths.

One purpose of the metering system with the preferential treatment for HOV vehicles is to encourage mode shift to HOV vehicles. The incentive is provided by (1) toll-free use of the bridge, and (2) elimination of delay associated with queueing at the toll booths and at the metering signals. The actual mode shift has not been measured.

Figure 22 presents the schematic diagram of the local area containing the candidate mainline metering at Site SF-2. The I-580 freeway segment downstream of this point has four lanes or five lanes throughout (each direction). One ramp is metered downstream of the interchange. Presently, there are three mainline lanes in the interchange area which could be widened by re-striping to four lanes in order to (1) permit one-at-a-time metering, and (2) provide additional storage. A to-be-constructed HOV structure over the median area would extend HOV lanes to a point just beyond the mainline meter so that HOV vehicles would be able to bypass the mainline queue. Several improvements (construction and metering) downstream of this site on I-580 are also planned to eliminate local congestion problems.

Route 24 is currently being extended southward toward downtown Oakland. Volumes on the connectors from Route 24 to I-580 Eastbound are expected to increase substantially, so that some sort of metering treatment in the Route 24/I-580 interchange area is desirable.

The current total vehicle demand through the interchange but before the Route 24 connectors is 4200 vehicles in the peak hour. This is expected to remain unchanged as this traffic derives primarily from the San Francisco/Oakland Bay Bridge which is currently at capacity. By restriping to four lanes, the non-HOV vehicles can be metered one at a time up to a rate of 900 vehicles per lane per hour. The several hundred vehicles which would queue at this point could easily be stored on the mainline and still be confined to the interchange area without adverse impact on other movements in the interchange.

Mainline metering would be expected to:

(1) Avoid downstream congestion which would otherwise develop when the Route 24 extension is completed;

(2) Place all queueing on one approach (the mainline) rather than have it exist on both the mainline and connectors. This would lead to a more consistent situation so that, with appropriate warning signs, drivers would not be surprised by queueing, and

(3) Present a contrast between HOV and non-HOV travel times, thus encouraging a mode shift.

Actually, non-HOV drivers would have both the mode shift option and a reasonable alternate route option -- MacArthur Boulevard which parallels I-580 just to the north. Ample warning upstream of the mainline queue could be given so that drivers could leave the freeway to get to MacArthur. Further, there is a simple return to the freeway downstream of the metering site.

Figure 23 depicts the area of site SF-4 in San Jose. Both NB and SB directions of Route 17 have on ramp metering (AM for NB; PM for SB); I-280 is metered in the WB direction. Route 17 ramp metering extends beyond the Route 17/I-580 in both directions; I-280 ramp metering is initiated just beyond this interchange. There is interest in implementing connector metering on the connectors from I-280 to both NB and SB Rte 17.

The on-ramp metering system currently in place on Route 17 is generally quite effective. However, the uncontrolled connector demand does, on occasion, lead to substantial congestion immediately downstream of the interchange in both directions. The connector from I-580 WB to Route 17 NB is in fact currently metered, as this approach is fed to a collector-distributor road where it merged with on-ramp traffic and metered. If the I-580 EB to Route 17 NB connector were metered, the congestion which now develops on Route 17 could be moved to this connector. The geometric design of this connector (see Figure 23) provides ample storage for vehicles and ample sight distances for advance warning signs. As the congestion presently experienced is moderate, connector queueing could be contained within the available storage.

The congestion which develops on Route 17 SB, immediately south of the interchange, is more severe, and is directly related to the heavy connector demands. Connector geometrics here are also good. Further, there are good alternate routes to which connector traffic could divert by exiting the freeway upstream of the interchange and entering Route 17 at the first on-ramp downstream of the interchange. As the present congestion tends to be localized to the freeway section upstream of this on ramp, and there is heavy off-ramp flow at this location as well, diversion of the connector traffic in this fashion should be quite effective.

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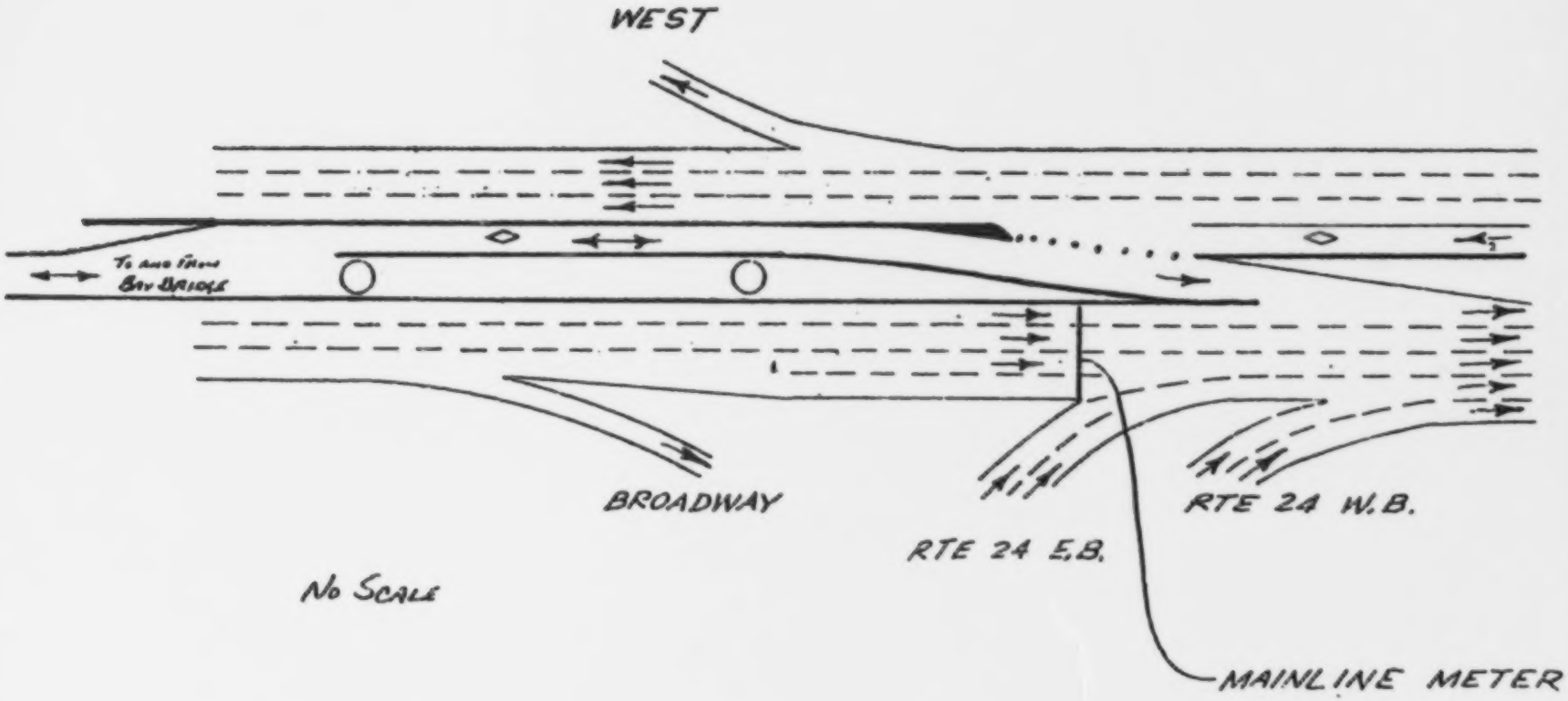

Figure 22. SF-2 Site with Possible Mainline Metering at Route 24 Interchange

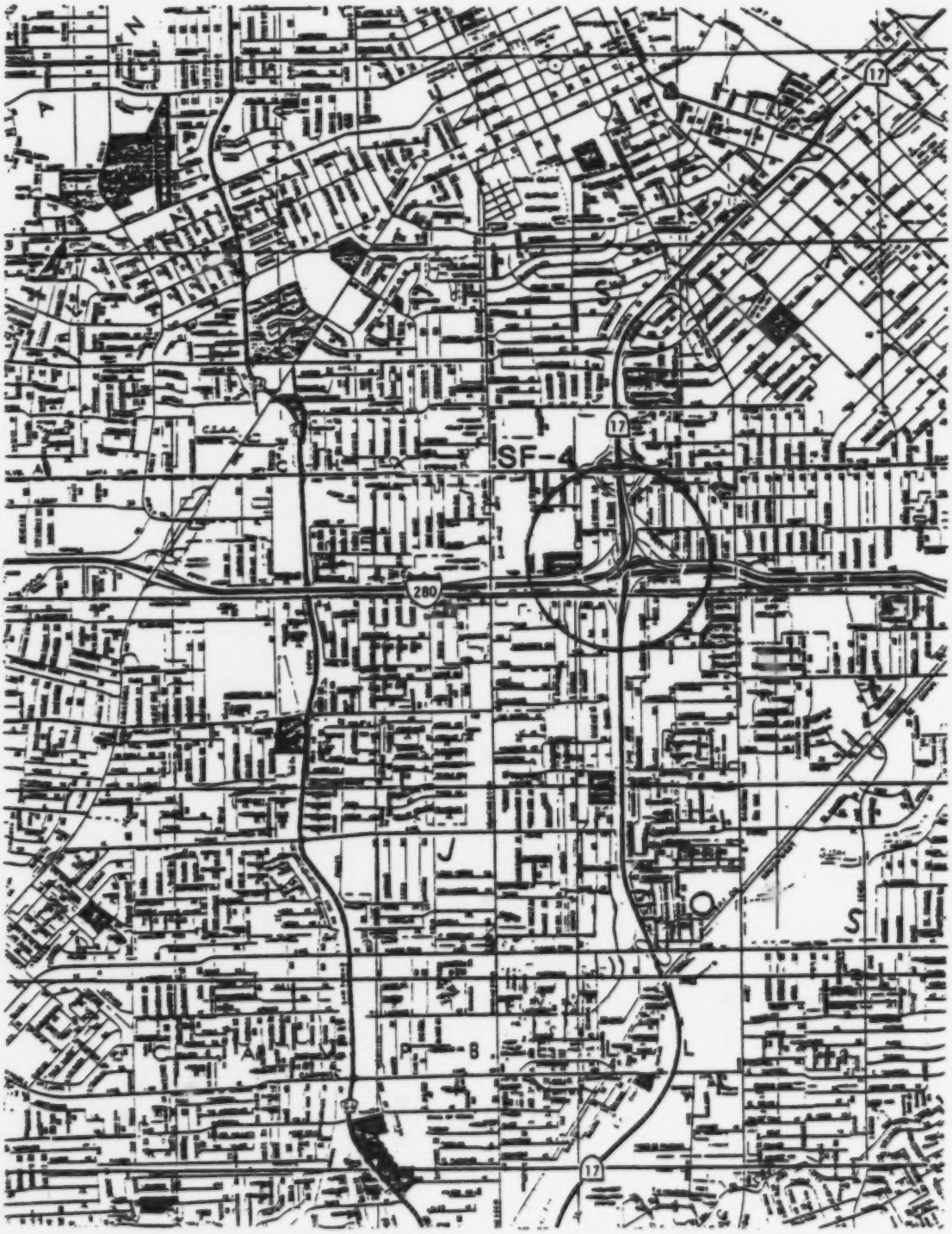

Figure 23. Route 17 in San Jose Containing Site SF-4

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3.2.4 Minneapolis Area Sites

Two interchange sites (MN-2 and MN-3) were visited in the Minneapolis area. Both are contained within the segment of I-35W extending from the Minneapolis CBD southward to Bloomington; locations of these sites are indicated in Figure 24. A system metering plan, including both on ramps and connectors, is in place for both directions of I-35W. At the MN-2 site, the interchange of I-94 and T.H. 65 (freeway connector to SB I-35W), the connector from EB I-94 to SB T.H. 65 is metered. At the MN-3 site, all four connectors from I-494 to NB and SB I-35W are metered.

Traffic demand on I-35W is quite heavy, but the system metering plan has been very effective in keeping congestion off the freeway and in producing travel time benefits in this freeway corridor. The connector demands in the PM peak period at the I-494/I-35W interchange are very heavy. If these connectors were not metered, the remaining ramp meters could not prevent freeway congestion. See Appendix A for further descriptions.

PM peak traffic on the SB I-35W freeway segment containing these Minneapolis area sites was used as a basis for one of the five cases investigated in the latter portion of this study.

3.2.5 Houston Area Sites

Two sites (HO-2 and HO-4) associated with the Route 59 (Southwest Freeway) in Houston were visited. The locations of these sites are indicated in Figure 25. AM peak inbound traffic is of concern here. The HO-2 site is a candidate mainline metering location at Bissonnet; the HO-4 site is the I-610/Route 59 interchange.

Figure 9 of the previous section presents the freeway segment currently under ramp metering control, with the Bissonnet mainline metering location being at the lower left. The freeway is three lanes (each direction) from Bissonnet to the area of the I-610 interchange, and four lanes thereafter. There is a frontage road paralleling the freeway, except that there are discontinuities at a rail crossing. The location of the bottleneck in 1979 was in the vicinity of the railroad crossing immediately downstream of Hillcroft. Since 1979, the increase in traffic demand has moved the bottleneck to the vicinity of Bissonnet.

Ten ramps, from Fondeau to Kirby Drive, are currently metered on the inbound Southwest Freeway. The ramps are of the relatively short slip ramp design, so that queueing typically extends back up onto the frontage road. This generally does not create a significant operational problem. The continuing increase in mainline volumes upstream of Fondeau will be addressed by an upstream extension of metering. The uncontrolled mainline demand will likely remain a problem, however.

Mainline metering in the vicinity of Bissonnet has been suggested as a means to alleviate the freeway congestion. At many intersections of the freeway with major arterials, including Bissonnet, the freeway is locally elevated. This situation provides an excellent opportunity for locating mainline metering on the upgrade with excellent viewing available to approaching motorists. Specific plans concerning metering operation, metering rates and advanced warning have not been developed.

Potential benefits of mainline metering at this location are:

(1) Better access for High Occupancy Vehicles (if an HOV lane and preferential metering were implemented),

(2) Improved flow through the bottleneck area on the mainline,

(3) Improved effectiveness of ramp metering downstream of the mainline metering location, particularly at high demand ramps, and

(4) Diversion to good alternate street routes.

AM peak traffic on this inbound segment of Route 59 was used as the basis for one of the five cases investigated in the latter portion of this study.

3.2.6 Washington, D.C. Area Sites

Two sites (CA-1 and CA-4) in the Washington, D.C. area were visited; their locations are indicated in Figure 26. Both sites involve mainline metering.

The CA-1 site is at the merge point of the George Washington and Spout Run Parkways. A schematic of the site is provided in Figure 27. In this situation, the two-lane Spout Run Parkway merges into the two-lane southbound George Washington Parkway. Currently, both the parkway and the ramp are narrowed to one lane by pavement markings just upstream of the merge area. This requires traffic from the George Washington Parkway to enter the merge area in the left lane and traffic from the Spout Run Parkway to enter the merge area in the right lane.

Downstream approximately 3/4 mile from this site, the GW parkway passes on a curve under the Key Bridge. These geometrics and sight conditions represent a bottleneck. Further downstream, the exit ramp to the Theodore Roosevelt Bridge handles a large volume so that free flow is resumed at this point. The volume downstream of the merge is constrained by the bottleneck in the vicinity of Key Bridge, typically leading to a queue which

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Figure 24. Location of Sites Visited in the Minneapolis Area

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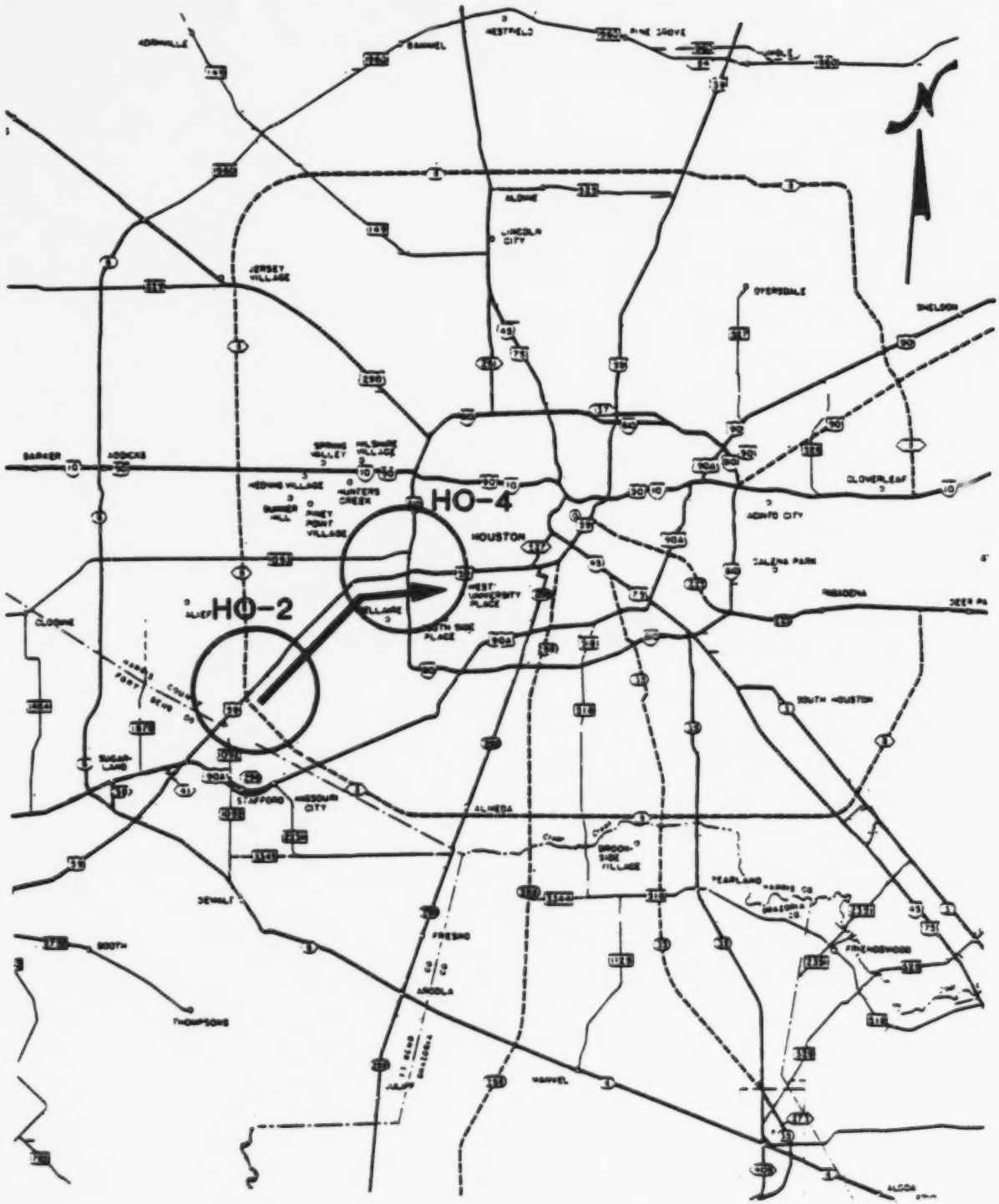

Figure 25. Houston Area Sites

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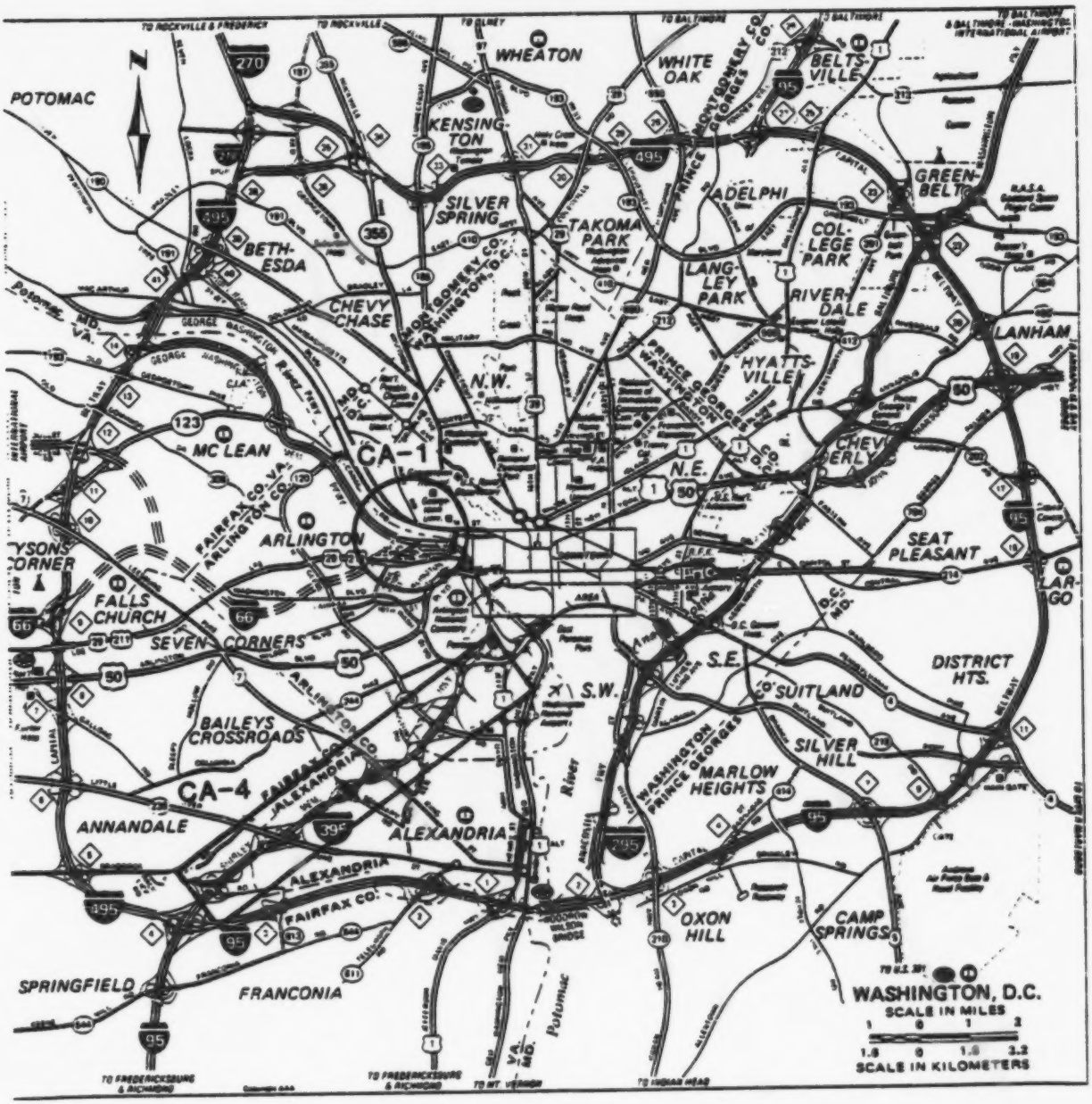

Figure 26. Location of Capitol Area Sites

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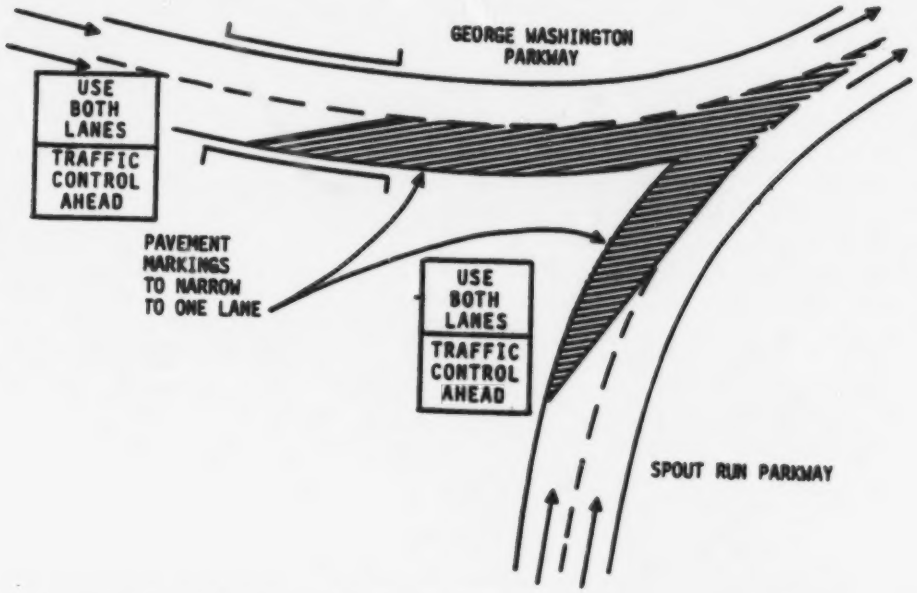

Figure 27. Merge Area of George Washington/Spout Run Parkways (Site CA-1)

backs up to the GW/SR merge area. The traffic volumes on the GW Parkway during the period 6:00-10:00 AM exceed the capacity of the single lane available (due to the pavement markings).

In the peak period, both lanes on each facility are used and the intersection is controlled by a park policeman who alternately switches the right of way between the George Washington and Spout Run Parkways. During control, advance warning signs on each approach advise motorists to use both lanes of the approach (and that traffic control is in effect). The park policeman initiates control between 6:30 and 7:00 AM on weekdays after locating a suitable gap on one of the approaches. Thereafter, typical practice is to provide access to GW Parkway traffic for five minutes, then access to SR Parkway traffic for two and one-half minutes. Alterations to this policy are made by the park policeman when traffic conditions are affected by disablements on either approach or when the queue extending from the Key Bridge bottleneck backs up into the merge area. In transitioning between GW and SR parkway movements, the park policeman uses a flare to alert motorists and bring vehicles to a stop. As most drivers are commuters, drivers on the other approach know to commence their movement at this time so that essentially no time is lost in the merge area.

Traffic demands at this location are highly seasonal, being light during the summer, very heavy during the fall and through early December, light during late December, and very heavy until summer again.

The factors cited indicate that an automated operation would require many features beyond the use of traffic signals on the two approaches, including:

(1) Turn on procedure which was responsive to traffic conditions, initiated presentation of the advance warning signs, and brought vehicles safely to a stop from a previously uncontrolled situation;

(2) Variable metering rates in response to variations in demand, including those induced by disablements; and.

(3) Enforcement measures, at least during the initial period of implementation.

The effect of metering (whether the existing manual technique or a new automated technique) is principally to provide access to the merge area which is balanced with the demand. In the absence of metering and with only one lane available to each approach, the capacity for the GW approach is substantially less than the demand, whereas the demand on the SR approach is less than the available capacity. A further, local effect, may be to improve throughput in the merge. However, the downstream bottleneck (at Key Bridge) limits any possible benefit from this improvement.

The CA-4 site is a candidate mainline metering at the southern end of a NB (or inbound) segment of I-395 (Shirley Highway) in Virginia. This segment and the candidate mainline metering location are illustrated in Figure 8 of the previous section. At present, there is no metering, but plans are currently

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being developed for on-ramp metering at locations within this segment. There are no plans to implement mainline metering.

AM peak traffic, largely destined for Washington, D.C., or the Pentagon, is very heavy and regularly leads to congestion, due to a general accumulation of demand over several upstream on ramps in excess of capacity and specifically due to a very heavy merge at Shirlington. This congestion extends from Glebe Road at the downstream end to Duke Street at the upstream end. Alternate routes for many drivers are nonexistent as they must use the 14th St. bridge at the downstream end of this segment to get to Washington. Under present conditions queueing at on ramps within the congested area is extensive. Egress to destinations before the 14th St. bridge is also obstructed. Mainline metering occurs as a candidate at the far upstream end of this segment (Edsall St.) because:

- Diversion from the freeway of vehicles with destinations in Virginia would make capacity available for vehicles destined for Washington (and for whom there is no reasonable alternate), and

- This location has a very substantial storage capacity so that the obstructive congestion currently present on the freeway could be moved to this location, with potential travel time benefits.

AM peak traffic on this inbound segment of I-395, with the candidate mainline metering, was used as the basis for one of the five cases investigated in the latter portion of this study.

3.3 Conclusions

Information gained from the site visitations and from available reports leads to some general conclusions pertaining to the implementation of connector and mainline metering, and to further specific conclusions concerning detailed aspects of metering design and expected impacts. First, we address the general conclusions of broad scope.

- Metering of access to point facilities (bridges and tunnels) has been successfully implemented. In particular, metering of the access to the San Francisco/Oakland Bay Bridge has successfully alleviated congestion on the bridge and has produced passenger travel time benefits. Design of such metering is relatively straightforward as one need only account for a single capacity constraint associated with the facility. There is an opportunity to reap passenger travel time benefits by providing preferential access for High Occupancy Vehicles. More complex, traffic-responsive metering can be implemented to provide better utilization of the available capacity.

- Connector metering has been successfully implemented. In San Diego and Minneapolis, a total of seven different freeway-to-freeway interchanges have been treated with connector metering installations. Noteworthy aspects of these implementations are:

  - Connector metering was implemented as a part of a system metering plan involving ramp metering. In San Diego, the three interchanges with connector metering installations are all part of a segment of the Rte 94 freeway under such system metering. In Minneapolis, connector metering has been implemented at two interchanges within a segment of the I-35W freeway.

  - Demand on the metered connectors is high, and formed a substantial fraction of the total demand at the point of entry to the freeway. In most instances, if a connector was not metered, congestion of the freeway would result.

  - The manner of implementation of connector metering is essentially the same as for ramp metering, except for the necessary addition of advance warning signs.

  On the other hand, operational personnel in the Los Angeles area have met sufficient adverse reaction on the part of public officials, so that they have not been able to go forth with similar plans for implementing connector metering.

- Freeway mainline metering (other than the manual George Washington Parkway metering) has not yet been implemented, and its consideration is cautiously undertaken if at all. Mainline metering is generally regarded as a distinguishable and radically different form of metering. Along with connector metering, it involves imposition of control on the freeway itself, a factor which distinguishes it from on-ramp metering, in a legal sense in certain areas and in terms of public perception in all areas visited. There is evidence, however, that mainline metering can be beneficial in traffic engineering terms. A manual metering procedure associated with the merge of the George Washington and Spout Run Parkways in the Washington D.C. area has operated for many years. Accidents have not been a problem, and the operation successfully provides access balanced with demand. Secondly, the

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metering installation at the 94/125 interchange in San Diego is in a sense a mainline meter. The safety issue which can be raised was successfully addressed there with effective, but not really very elaborate, advance warning signs. And from a technical standpoint, mainline metering has the potential to greatly reduce delay related to freeway congestion. At this point in time, however, the reality of the situation in all areas visited where this possibility was discussed is that the expected public reaction would be severely adverse.

Additional important conclusions have been drawn pertaining to technical issues.

- Diversion of traffic from metered locations is an important and perhaps crucial aspect of the success of any form of metering. Metering, where it is successful, has the effect of causing drivers to make better use of the entire freeway corridor capacity. If substantial diversion does not occur, queueing on the freeway is merely moved to other locations. Due to generally limited storage capacity at metered locations, this can in turn merely shift the deleterious impacts to surface streets or other freeways.

- Adequate capability for storage of queues is a primary aspect of metering plan design. Metering at on ramps, on connectors or on the mainline generates queues which must be properly accounted for. In the instance of connector metering, the geometric characteristics of the connector and of the upstream freeway segment define the operationally effective storage capacity, i.e., the area where vehicles can be stored without adverse impact on flow on the feeding freeway. Short-radius connectors which are present in cloverleaf interchange designs allow very little storage and may as a result not be suitable locations for metering. Designs with very long connector segments, on the other hand, can provide very substantial amounts of storage. In some instances it is possible via operational changes (e.g., closing of an on or off ramp) and or limited restriping or reconstruction to increase queue storage to needed levels. Mainline metering at certain locations can provide a very substantial amount of storage. In this instance, it is desirable to maintain the queue in an area where it will not obstruct egress to an off ramp or connector.

- Traffic demand data typically available for metering plan designs are mainline, entrance and exit volumes over time slices of fifteen minutes. Origin-destination data are not typically gathered due to the attendant expense. However, acceptable techniques for generating estimates of OD demand volumes are available [ELD073] and have been used by several operating agencies.

- Present practice is to assume that metering does not impact the capacity of the merge area. Metering has the effect of breaking up platoons on metered approaches, thereby presenting to the merge area a more uniform flow of vehicles. This fact suggests that metering might therefore allow the merge area to service a greater volume of vehicles. Some support for this notion was provided in discussions with operational personnel, but the situations where the effect might be significant were thought to be limited to weave areas. While such situations are fairly common in the region including a connector and a downstream off ramp, the prevailing view was that the beneficial impact is probably quite small, and prudent design practice is to assume that no such benefit will occur.

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4.0 EVALUATION PROCEDURES

Existing implementations of freeway-to-freeway connector metering have been made in the larger context of connector and on ramp metering over a freeway segment typically involving several to a score of metering locations. Future mainline metering and connector metering are expected to be implemented in the same type of environment. The purpose of this section is to present the details of the metering design and performance evaluation procedures for candidate implementations of both mainline and connector metering in a freeway segment, with associated on ramp metering.

4.1 Modeling and Metering Design Issues

Several important issues arise in selecting the analysis approach:

(1) It is desirable to model the "before" situation, where congestion on the freeway typically exists.

(2) It is desirable to provide an integrated on ramp-connector-mainline metering design technique which reflects current practices.

(3) It is desirable to model the impacts of a planned metering system design in terms of travel times and queues at metering locations.

(4) It is desirable to model the expected diversion at metering locations.

The scope of this project forces certain compromises on the approach:

(1) Accurate modeling of freeway congestion requires a dynamic simulation, of the type provided by FREQ [ORTH73] INTRAS [WICK77] or FREFLO [PAYN78]. Where freeway congestion is "localized", i.e., does not extend over any exit ramp, the first and principal effect of metering is merely to move the congestion (and attendant delay) from the freeway to the metering locations, without any impacts upon total travel time. However, where freeway congestion is more extensive, and does obstruct egress, there are additional delay benefits of ramp metering. Dynamic simulation models are not used in this study. One immediate consequence, therefore, is that the benefits of metering related to these additional delays incurred in extensive freeway congestion have not been accounted for. However, the approach developed here will allow a measurement of travel times in the "before" situation under the assumption of "localized" freeway congestion.

(2) Integrated metering design schemes are available which are simple to employ and correspond closely to much of existing practice. In particular, a type of maximum input technique can be easily executed. This choice excludes potentially more effective, but computationally more complex design techniques based upon linear programming [MASH75]. Further, it has been observed that design practice varies substantially. We have chosen one representative design technique, rather than attempt to provide multiple design approaches. An important feature of this design technique, not available even in the more complex linear programming approaches, is the explicit consideration of vehicle storage constraints at metering locations.

(3) A simple, quasi-stationary model of traffic flow has been identified which provides the necessary travel time, metering location delay and queue length measures.

(4) Diversion, or route choice, is a complex phenomena, which can involve: (a) diversion to alternate street routes, (b) diversion to a route consisting of an alternate street route segment, followed by a freeway segment, and (c) temporal diversion. The latter two are particulary complex, but, also probably involve less of the demand than the simpler diversion of type (a). We have developed detailed procedures to account for this "short trip" diversion, but do not consider diversion of the latter two types.

The methods which have developed are based upon a decomposition of demand by destination. This choice, it is believed, provides essential accuracy in predicting traffic patterns and is critical to the procedures we have detailed for short trip diversion.

There will be a natural role for future simulation studies. Simulation models, such as FREQ [ORTH73], INTRAS [WICK77] and FREFLO [PAYN78], have the required dynamic characteristics to provide representations of congested "before" simulations not possible with simple analytic models. Further, these models will provide more accurate predictions of traffic patterns with metering plans than can be provided by the quasi-stationary analytic models developed for use in this study.

The procedures developed for the analysis in this study will serve two purposes:

(1) generation of analysis results which will reveal the significant qualitative features of traffic situations pertinent to the efficacy of mainline and connector metering, and

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(2) a basis for design of integrated system metering.

These procedures can be distinguished as a preliminary step of OD estimation, followed by system metering design and impact evaluation.

4.2 Estimation of Origin-Destination Demand Volumes

The metering design and impact methods adopted for this study include representation of the critical effect of diversion. As such, they necessitate an accounting of the distribution of destinations of the vehicular demand presented to the freeway system. This, in turn, leads to a requirement for origin-destination (OD) data.

The present practice is for freeway operational personnel to estimate OD patterns from volume data rather than expend the considerable effort otherwise necessary to collect OD data. Reflecting this, we incorporated an OD pattern estimation procedure into the analysis approach. Specifically, the proportional distribution trip distribution method was selected as the basis for this procedure. This choice resulted from an assessment of available methods, and was aided by available studies performed at the Institute for Transportation Studies (ITS) at U.C. Berkeley [CHAN80, WILL80]. This method is the basis of the SYNODM code developed at U.C. Berkeley [ELD073], and is currently used by personnel in MNDOT and the San Diego district of Caltrans (and perhaps by others). The ITS studies indicated that the proportional distribution method represented a desirable tradeoff between accuracy of results and data collection requirements. In particular, the required data, on and off ramp volumes, are routinely collected in freeway operations studies.

We have used a slight modification to the pure proportional distribution method in which certain OD volumes are prescribed. This will accommodate situations in which:

(1) certain routes are known to be little used, e.g., a route involving exiting the freeway at a location immediately downstream of the entrance location; and

(2) a heavy or otherwise important route flow has been measured; e.g., the distribution of destinations for demand on a connector.

The resultant principle for OD estimation is stated as follows:

> The relative fractions of the volume exiting at a location as distinguished by origin are the same as the relative fractions of the freeway volume approaching that location. Where certain OD volumes are prescribed, these are first accounted for, and the principle of proportional distribution is applied to the remainder of the volume, i.e., those fractions whose origins are not involved in the prescribed OD volumes.

4.2.1 Details of Modified Proportional Distribution Method

The proportional distribution method is easily prescribed using the following notation, as illustrated in Figure 28:

q_{ik}	component of freeway volume at location k which originated at location i
f_i	on ramp volume at location i
g_j	off ramp volume at location j
O	set of indices of locations of off ramps
D	set of indices of locations of off ramps
	} assumed disjoint
OD	set of O-D pairs for which volumes are prescribed
d_{ij}	estimated volume from origin i to destination j
$\bar{d}_{ij}$	prescribed volume from origin i to destination j

The upstream freeway volume, q_{11}, the on-ramp volumes and off-ramp volumes are assumed to be available data. In some cases, certain OD volumes will be prescribed. For

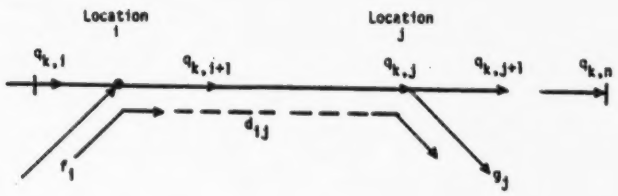

Figure 28. Notation for OD Estimation

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example, if it is assumed (or known) that none of the traffic entering at a location i will exit at the immediately downstream off ramp at location i+1, we would prescribe $d_{i,i+1} = 0$. Further, if data are collected for certain important OD pairs, the corresponding values d_{ij} would be prescribed.

To implement the principle of proportional distribution, modified to account for prescribed OD volumes, one executes calculations for locations in an ordered sequence starting at the upstream end, location 1, through location n-1. Each location is one of three types: (1) entrance present, (2) exit present, or (3) no entrance or exit present. Corresponding to these three types, the following calculations are made:

(1) entrance present at location i ($i \in O$):

$$q_{k,i+1} = q_{k,i}, \quad k<i$$

$$q_{i,i+1} = f_i$$

(2) exit present at location i ($i \in D$):

Account for prescribed OD volumes, k such that $(k,i) \in OD$:

$$d_{ki} = \bar{d}_{ki}$$

$$\bar{g}_i = g_i - \sum_{j \in (k,j) \in \overline{OD}} \bar{d}_{kj}$$

$$q_{k,i+1} = q_{k,i} - d_{ki}, \quad (k,i) \in OD$$

Account for remaining fractions, k such that $(k,i) \in OD$

$$d_{ki} = \bar{g}_i \, q_{ki} \Big/ \sum_{j \in (k,j) \notin OD} q_{kj}$$

$$q_{k,i+1} = q_{k,i} - d_{ki}$$

(3) no entrance or exit present at location i:

$$q_{k,i} = q_{k,i+1}$$

4.2.2 Example Application of Procedure for Estimation of Origin-Destination Demand Volumes

Figure 29 presents the schematic and data for the example.

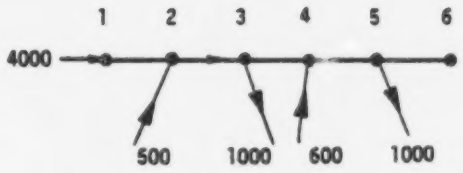
Location 1

The upstream volume, 4000 veh/hr, is treated as an entrance volume. Hence:

$$q_{12} = f_1 = 4000 \text{ veh/hr}$$

Location 2

This is an entrance location. Hence,



Prescribed OD volumes:
$\bar{d}_{23} = 0$, $\bar{d}_{45} = 300$, $O = \{1,2,4\}$, $D = \{3,5,6\}$

Figure 29. Schematic and Data for Example

$$q_{13} = q_{12} = 4000$$

$$q_{23} = f_2 = 500$$

Location 3

This is an exit location. We first account for the prescribed origin-destination demand volume whose destination is Location 3, $\bar{d}_{23} = 0$.

$$d_{23} = \bar{d}_{23} = 0$$

$$\bar{g}_3 = g_3 - \bar{d}_{23} = 1000 - 0 = 1000$$

$$q_{24} = q_{23} - \bar{d}_{23} = 500 - 0 = 500$$

Next we account for the remaining components of the freeway volume, i.e., those components for origins other than that of the prescribed OD demand volume. In this case, the only remaining component is for origin location 1. Hence

$$d_{13} = \bar{g}_3 \, q_{13}/q_{13} = \bar{g}_3 = 1000$$

$$q_{14} = q_{13} - d_{13} = 4000 - 1000 = 3000$$

Location 4

This is another entrance location.

$$q_{15} = q_{14} = 3000$$

$$q_{25} = q_{24} = 500$$

($q_{35} = q_{34} = 0$ since Location 3 is not an origin.)

$$q_{45} = f_4 = 600$$

Location 5

This is another exit location, with one prescribed origin destination demand volume, i.e., $\bar{d}_{45} = 300$. We first account for this:

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$$d_{45} = \bar{d}_{45} = 300$$

$$\bar{g}_5 = g_5 - \bar{d}_{45} = 1000 - 300 = 700$$

$$q_{46} = q_{45} - d_{45} = 600 - 300 = 300.$$

Next we account for the two remaining components corresponding to origin Locations 1 and 2:

$$d_{15} = \bar{g}_5 \, q_{15}/(q_{15} + q_{25})$$

$$= 700(3000)/(3000 + 500)$$
$$= 600$$

$$d_{25} = \bar{g}_5 \, q_{25}/(q_{15} + q_{25})$$

$$= 700 \, (500)/(3000 + 500)$$
$$= 100$$

$$q_{16} = q_{15} - d_{15} = 3000 - 600$$

$$= 2400$$

$$q_{26} = q_{25} - d_{25} = 500 - 100$$

$$= 400$$

Location 6

This final location can be treated as an exit location. However, it is immediately evident that the origin-destination volumes coincide with the freeway component volumes, so that

$$d_{16} = q_{16} = 2400$$

$$d_{26} = q_{26} = 400$$

$$d_{46} = q_{46} = 300$$

These results can be conveniently collected in a familiar tabular format, Table 9.

4.3 Metering Design and Evaluation

This section delineates the metering design and evaluation procedures. First, we identify the principles of the underlying model and of the metering design procedure.

4.3.1 Modeling and Metering Design Principles

The model adopted here is quasi-stationary. The control period is divided into time slices. Volumes, both demands and those which result on the freeway, are taken to be constant over time slices. Freeway congestion is not modeled*; it is assumed that metering rates are chosen so that resultant freeway volumes do not exceed capacities. However, connector and on ramp queueing is modeled and generally will occur where demands exceed metering rates. Queues are carried over from one time slice to the next.

Components of traffic volumes and the queues are distinguished by destination (exit ramp or downstream end of the freeway segment). Two modeling options are described with respect to diversion: (1) no diversion, so that excess demand queues at the metered location; and (2) short trip diversion, in which that portion of the demand which has a faster alternate route diverts.

Metering design is based upon maximization of on ramp inputs (in a sequence from upstream to downstream) subject to constraints upon metering rates and vehicle queues; this choice of technique is (1) simple to use, (2) coincides with practice in several operational agencies (except for the vehicle storage constraint), and (3) coincides with or approximates the objective of minimization of system travel time. Other techniques might be investigated; limiting the techniques was intended to allow focus on issues critical to mainline and connector metering, as opposed to an investigation of ramp metering techniques.

*The specific nature of the model limitation is that queueing be limited to entrance nodes of the freeway network. As we discuss subsequently, even with this limitation, a useful measurement of freeway congestion, which results when no metering is applied, can be extracted.

Table 9. Estimated Origin-Destination Volumes for Example

ORIGIN	DESTINATION 3 OFF 1	DESTINATION 5 OFF 2	DESTINATION 6 DOWNSTREAM	TOTAL
1 UPSTREAM	1000	600	2400	4000
2 ON 1	0	100	400	500
4 ON 2	0	300	300	600
TOTAL	1000	1000	3100	

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Despite the simplicity of this approach, this metering design approach has important operational features - specifically, consideration of vehicle queue constraints at metering locations and of diversion - not previously treated as an integrable part of the design procedure.

4.3.2 Overview of the Metering Design and Evaluation Procedure

The analysis procedure is depicted in Figure 30. The major steps of the procedure are:

(1) Initialization: Time step index set to 1 and initial queues specified (typically empty).

(2) Preliminary (Minimum) Metering Rate Assignment: Minimum metering rates are determined as the greater of (a) a minimum rate necessary for effective functioning of a metering signal, and (b) the minimum rate which (after accounting for diversion) assures that vehicle storage constraints will not be violated. These are then assigned to each metering location, and associated freeway volumes and available capacities (orginal capacity minus projected freeway volumes) are computed. If any projected freeway volume exceeds capacity (so that the available capacity is negative), there is no feasible design. The analysis procedure must be interrupted and the specified minimum metering rates and vehicle storage constraints re-examined.

(3) Compute Metering Rates and Queues: The metering rates are selected to maximize inputs, subject to constraints on the projected freeway volumes represented by the available capacities; corresponding queues at metering locations are computed based upon no diversion.

(4) If no short trip diversion is being considered, travel time performance measures (freeway travel time and on ramp delays) are computed.

(5) If short trip diversion is being considered, the user-optimization principle is applied at each metering location to determine the amount of diverted traffic and to adjust the queues.

(6) Performance measures, including those associated with diversion, i.e., diverted traffic travel time are computed.

Steps 2,3,4 or 2,3,5,6 are repeated for each time slice.

Subsequent sections provide details of the computational procedures for steps 2,3,4,5 and 6 noted above.

This procedure applies equally where mainline and/or connector metering are to considered. The restrictions that do apply are:

(1) the freeway segment can be represented as a single, linear network;

(2) queueing occurs only at metering locations.

A metered freeway-to-freeway connector can therefore be represented at any identified metering location along the network. Mainline metering at the upstream end of a segment can be handled as a metered access where the merging volume freeway is zero, e.g., as illustrated in Figure 31.

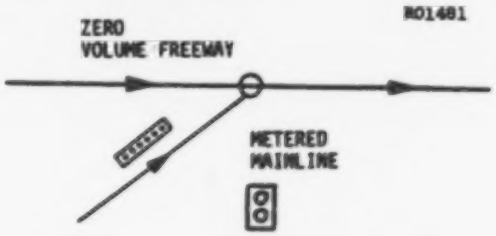

Figure 31. Technique for Considering Mainline Metering

4.3.3 Details of Metering Design Procedure

4.3.3.1 Preliminary (Minimum) Metering Rate Assignment

Minimum metering rates are generally necessary due to driver behavior (unduly long cycles often lead to substantial violations), and may otherwise be specified to accommodate a fair distribution of access to the freeway. In addition, as entrance location queues build up, it is necessary to assure that the final metering rate assigned is sufficient to avoid violation of vehicle storage constraints. The first step in the metering design and evaluation procedure is the determination of these minimum rates, and the computation of freeway capacities available after projected volumes associated with these minimum rates are accounted for.

Demand and freeway volumes are distinguished by components associated with distinct destinations (exit ramps, and downstream end of the freeway). Notation necessary for the procedure for assigning minimum metering rates is as follows:

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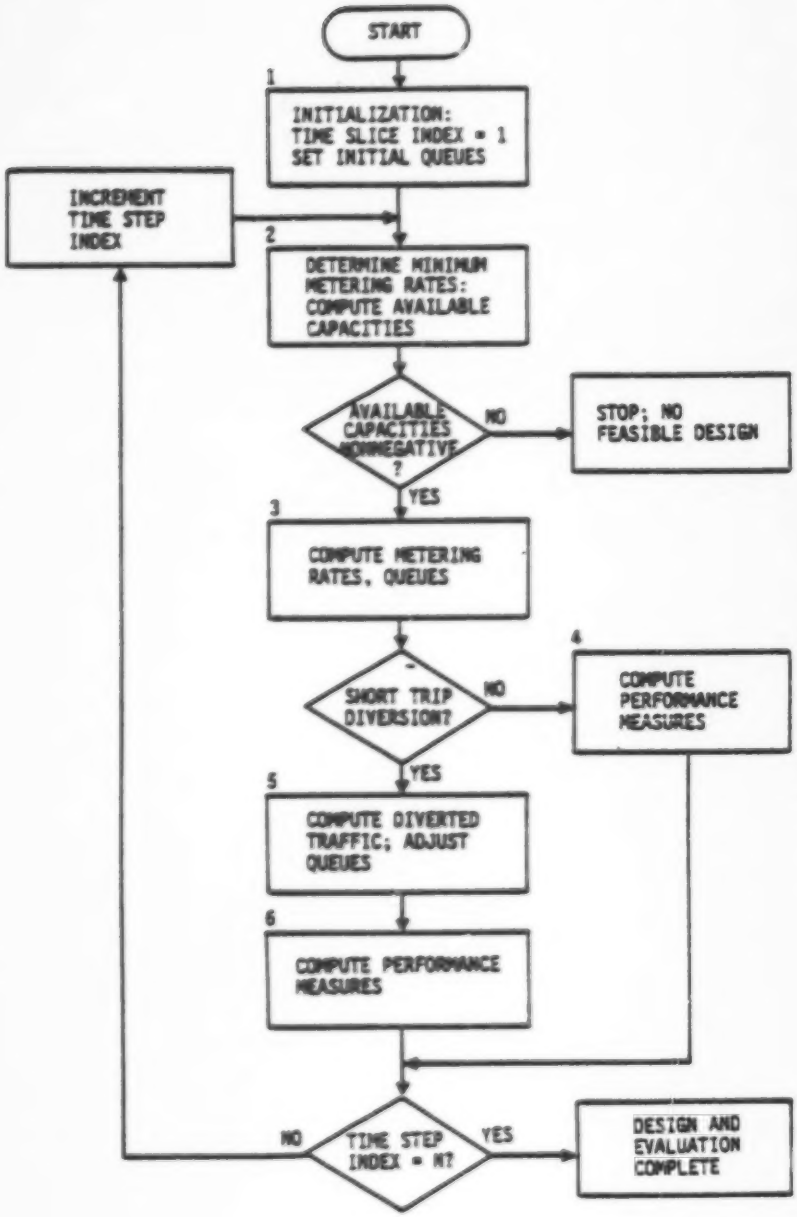

Figure 30. Flow Diagram for Metering Rate Design and Performance Evaluation

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T	time slice duration
q_j	total freeway volume at arriving location j, after preliminary (minimum) metering rate assignment
q_{ij}	component of freeway volume arriving at location j which originated at location i
c_j	freeway capacity at location j
e_j	available freeway capacity at location j
$v_{i,min}$	minimum metering rate at location i
$\overset{\bullet}{v}_{i,min}$	fixed minimum metering rate at location i necessary for effective metering operations
$v_{i,max}$	maximum metering rate at location i
v_i	metering rate at location i
$v^s_{i,min}$	variable minimum metering rate necessary to assure satisfaction of vehicle storage constraint at location i
Δv_i	increment to metering rate at location i above minimum
$f_{i,max}$	maximum entrance volume at location i
f_i	total demand at on ramp at location i
d_{ij}	component of demand at on ramp at location i destined for location j
a_{ij}	component of volume entering at location i destined for location j
λ_i	queue length (number of vehicles) at on ramp at location i at beginning of n^{th} time slice
λ_{ij}	number of vehicles at on ramp at location i destined for location j at beginning of n^{th} time slice
μ_i	number of vehicles requiring service at on ramp at location i by the end of n^{th} time slice
μ_{ij}	number of vehicles requiring service at ramp at location i destined for location j by the end of n^{th} time slice
$\lambda_{i,max}$	maximum number of vehicles which can be stored at location i

Calculations are made separately for each time slice. The notation below (Figure 32) refers to quantities for a time slice.

The procedure is executed in an ordered sequence beginning at the upstream end of the freeway segment (location 1) and concluding at the downstream end (location N-1). The objective of the procedure is to compute: (1) total projected freeway volumes, (2) remaining or available capacities, and (3) projected off ramp volumes.

At each location at which there is an on ramp, say at location i, the following computations are made. First, the number of vehicles requiring service by the <u>end</u> of the time slice is computed:

$$\mu_{ij} = \lambda_{ij} + d_{ij}T$$

$$\mu_i = \sum_{j>i} \mu_{ij} = \lambda_i + f_iT$$

Next, the minimum rate necessary to assure satisfaction of the vehicle storage constraint is determined. Where <u>no diversion</u> occurs, this is simply computed by

$$v^s_{i,min} = [\mu_i - \lambda_{i,max}]/T$$

Where diversion occurs, computation of the necessary minimum rate is considerably more

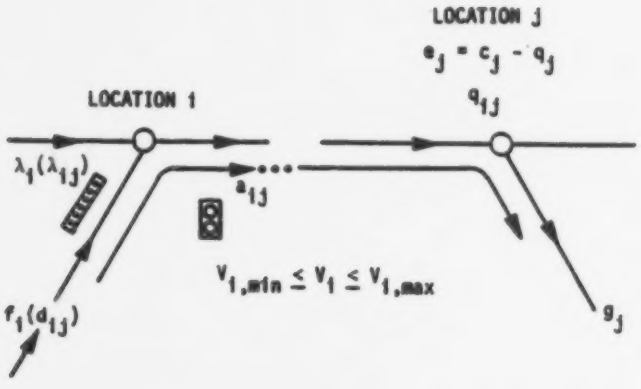

Figure 32. Notation for Metering Rate Assignment

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complex. Treatment of this case is deferred to Section 4.3.4.

For this time period, then, the mimimum metering rate is

$$v_{i,min} = \max[v^*_{i,min}, v^s_{i,min}]$$

Next the components of volume entering with a minimum metering rate are determined by:

If $v_{i,min}T<w_i$ (minimum metering rate does not satisfy entire demand)

$$a_{ij} = w_{ij}\, v_{i,min}/w_i$$

Else (minimum metering rate satisfies entire demand)

$$a_{ij} = w_{ij}/T$$

Freeway volumes at location j are given by

$$q_{ij} = \sum_{k\geq j} a_{ik} \quad , \quad j > i$$

$$q_j = \sum_{i<j} q_{ij}$$

Available capacity is then given by

$$e_j = c_j - q_j$$

Finally, after all on ramp specific calculations are made, the quantities q_j and e_j are computed for each location j, j=i+1,..., N, and the adjusted end-of-time-slice queues and exit volumes are computed via:

$$w_{ij} \leftarrow w_{ij} - Ta_{ij} \quad , \quad j>i$$

(where the symbol $\leftarrow$ means that the value of the expression on the right-hand side replaces the value of the variable on the left-hand side)

$$w_i = \sum_{j>i} w_{ij}$$

$$g_j \leftarrow g_j + a_{ij} \quad , \quad j>i$$

(indicates replacement of value).

These final computations should yield nonnegative values for the available capacities, e_j. If they do not, the minimum metering rates, vehicle storage constraints, and/or freeway capacities specified must be re-examined as the specifications do not allow a design which satisfies the capacity constraints.

4.3.3.2 Final Metering Rate Selection

Increments of metering rates above the assigned minimum rates are selected to maximize inputs in a procedure which sweeps along the freeway locations from upstream to downstream. The constraint on metering rates are (1) a priori specified maximums (due to geometric or metering operations limitations), and (2) available freeway capacity.

The following procedure is executed following minimum metering rate assignment for each time slice. At each location with an on ramp, say location i, the following computations are made:

(1) Compute maximum increment to metering rate

$$\Delta v_i = \min(f_{i,max} - v_{i,min}, w_i/T)$$

If $\Delta v_i = 0$, go to (6)

(2) Compute component volumes

$$a_{ij} = w_{ij}\Delta v_i/w_i$$

(3) Project component volumes downstream and check capacity constraint

$$q_{ij} = \sum_{k>j} a_{ik}, \; j>i$$

$$s_i = \min\,[s_{ij}]$$

with $s_{ij} = e_j/q_{ij}$

(4) Reduce increment to metering rate

set $\Delta v_i \leftarrow (1-s_i)\Delta v_i$

recompute a_{ij} from v_i by step (2)

recompute q_{ij} from a_{ij} by step (3)

(5) Compute new available capacity, new queues and exit volumes

$$e_j \leftarrow e_j - q_{ij} \quad , \quad j>i$$

$$\lambda_{ij}^{n+1} = w_{ij} - a_{ij}T \quad , \quad j>i$$

$$\lambda_i^{n+1} = \sum_{j>i} w_{ij} = w_i - v_iT$$

$$g_i \leftarrow g_i + a_{ij}, \; j>i$$

(6) Set total metering rate

$$v_i = v_{i,min} + \Delta v_i$$

4.3.3.3 Performance Measures

In the absence of diversion, two travel time measures are separately computed and then combined. Freeway travel time, for a time slice, is given by

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$$\frac{T}{S_f} \sum_{2 \le i \le N} q_i \ell_{i,i+1}$$

where T is the time slice duration, S_f is the assumed constant freeway speed, q_i is the total freeway volume approaching location i, and $\ell_{i,i+1}$ is the length of the freeway section between locations i and i+1. Ramp delay is given by

$$T\left[\frac{\lambda_i^n + \lambda_i^{n+1}}{2}\right]$$

where λ_i^n is the ramp queue length at the beginning of time slice n. The sum of these two measures is freeway corridor travel time.

4.3.4 Short Trip Diversion

Metering, largely because of associated queues, impacts the routing choices of drivers using the freeway system. The minimal impact is for drivers taking short trips to choose an alternate route on the nearby surface streets, because the travel time penalty - surface street versus freeway - is less than the delay incurred in waiting in queue at the metering location. More extensive impacts can also occur. For example, drivers may divert to an alternate route which includes entering the freeway at a downstream on ramp. However, our attention here is limited to the short trip diversion only, where we specifically assume that diverted vehicles never enter the freeway.

The principle used to identify that portion of the traffic demand which is expected to divert to an alternate route is that drivers select the alternate route if it is faster than the freeway route, including the wait in the queue. Figure 33 displays, in a general way, the quantities which enter into these computations: (1) alternate route travel time penalty, i.e., the excess of the travel time on the alternate route over the travel time on the freeway (not including the ramp delay); and (2) the delay at the ramp. These are shown in Figure 33 to depend upon the amount of diversion. That is, if no diversion occurs, the mean delay at the on ramp is greatest; it decreases as the amount of diversion increases. The least travel time penalty is incurred by those drivers with the shortest trips; thus they would divert first. The indicated "alternate route travel time penalty" is based on successively longer trips associated with successive groups of diverted traffic. As suggested in Figure 33, the amount of diverted traffic is the largest value of diversion volume for which the alternate route travel time penalty is less than the delay in the queue.

Additional notation necessary for specification of procedures for computing revised traffic patterns - reduced ramp queues and diverted traffic volumes - are as follows (also, see Figure 34):

$\delta_i(m)$	diverted traffic volume at location i, assuming all traffic destined for locations i+1 through m diverts
δ_{ik}	component of diverted traffic volume at location i destined for location k
m	location index of furthest downstream destination location for which traffic diverts
ℓ_{ij}	distance from location i to location j
S_f	freeway speed
S_a	alternate route speed

To quantify delay at the queue, we use the queue determined to exist at the end of the current time slice, λ_i^{n+1}, after accounting for the final metering rate selection, and the components of this queue, λ_{ij}^{n+1}. Hence, if diversion occurs for all trips not beyond location m, the diverted traffic volume is given by

$$\delta_i(m) = \frac{1}{T} \sum_{i<j \le m} \lambda_{ij}^{n+1}$$

If this much diversion occurs, the delay through the reduced queue incurred by an individual vehicle would then be

$$\text{delay} = \frac{1}{v_i}\left[\lambda_i^{n+1} - \delta_i(m)\right]$$

$$= \frac{1}{v_i} \sum_{j>m} \lambda_{ij}^{n+1}$$

The alternate route travel time penalty for trips with destination j is expressed as:

$$\ell_{ij}\left[\frac{1}{S_a} - \frac{1}{S_f}\right].$$

The diversion principle then determines the largest value of m such that

$$\ell_{im}\left(\frac{1}{S_a} - \frac{1}{S_f}\right) < \frac{1}{v_i} \sum_{j>m} \lambda_{ij}^{n+1}$$

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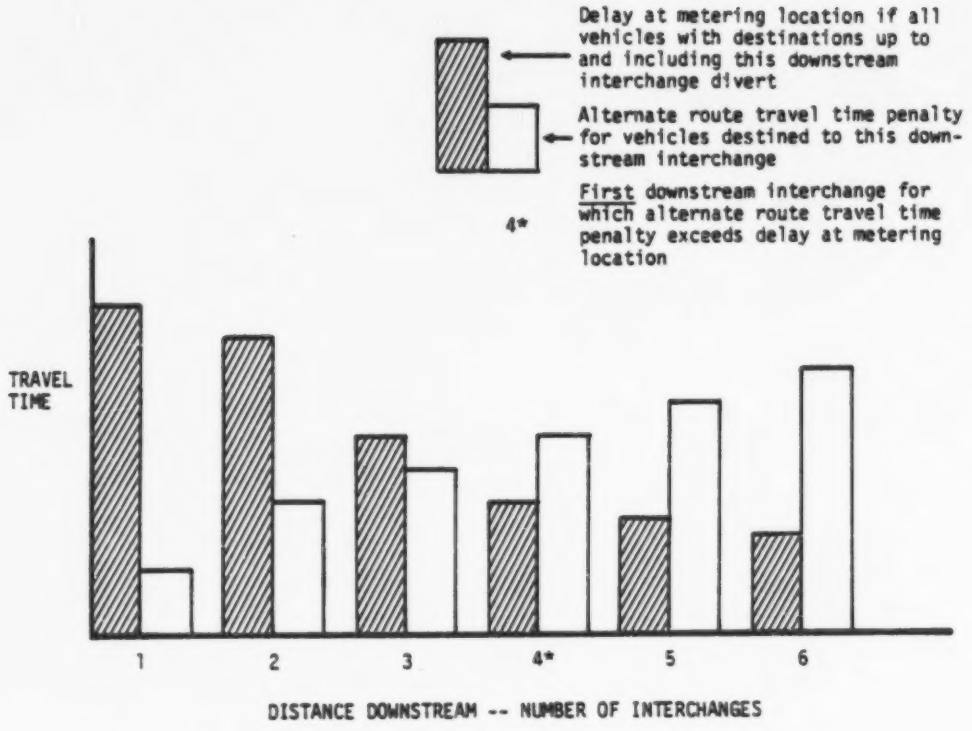
Delay at metering location if all vehicles with destinations up to and including this downstream interchange divert
Alternate route travel time penalty for vehicles destined to this downstream interchange
First downstream interchange for which alternate route travel time penalty exceeds delay at metering location
4*
TRAVEL TIME
1
2
3
4*
5
6
DISTANCE DOWNSTREAM -- NUMBER OF INTERCHANGES

Figure 33. Short Trip Diversion

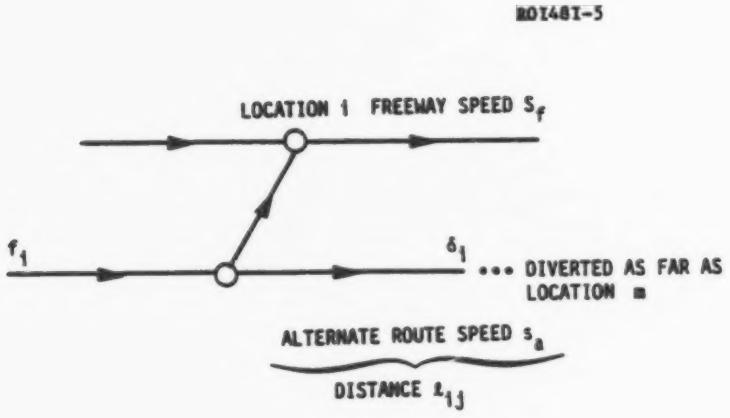

Figure 34. Notation for Short Trip Diversion Computations

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This determination in turn immediately defines the reduced queue and its components and the diverted traffic volume. Specifically

$$\lambda_i^{n+1} \leftarrow \lambda_i^{n+1} - \delta_i(m)$$

$$\lambda_{ij}^{n+1} = 0 \quad , \quad j \leq m$$

$$\delta_{ik} = \lambda_{ik}^{n+1} \quad , \quad i < k \leq m$$

Where there is short trip diversion, the travel time of diverted traffic must be accounted for. The appropriate expression, for time slice n, is

$$\frac{T}{S_a} \sum_{\substack{\text{locations } i \\ \text{with an on ramp}}} \sum_{k>i} \delta_{ik} \ell_{ik}$$

where S_a is the assumed constant alternate route travel speed, and δ_{ik} is the volume of traffic diverted at location i which is destined for location k.

The final point requiring attention is the computation of a minimum metering rate which assures satisfaction of vehicle storage constraints where diversion occurs. The complexity of this situation arises from the fact that the amount of diversion, and therefore the resultant vehicle queue length, depends upon the metering rate. The procedure, nonetheless, is reasonably straightforward.

With a metering rate of v_i (at location i), the components of the queue by destination which results at the end of the time slice, in the absence of diversion, are

$$\bar{\mu}_{ik}(v_i) = [1 - \frac{v_i T}{\mu_i}] \mu_{ik}$$

(assuming $v_i T \leq \mu_i$). If, further, diversion up to and including destination location m occurs, the resultant end-of-time-slice queue components, μ_{ik}, and total queue, μ_i, are given by

$$\bar{\mu}_{ik} = 0, \; k \leq m$$

$$\bar{\mu}_{ik} = (1 - \frac{v_i T}{\mu_i}) \mu_{ik}, \; k > m$$

and $\bar{\mu}_i = [1 - \frac{v_i T}{\mu_i}] \sum_{k>m} \mu_{ik}$.

Consequently, to satisfy the vehicle storage constraint, $\lambda_{i,max}$, requires

$$\lambda_{i,max} \geq [1 - \frac{v_i T}{\mu_i}] \sum_{k>m} \mu_{ik}$$

or $$v_i \geq v_{i,min}^s \equiv \frac{1}{T}[1 - \lambda_{i,max} / \sum_{k>m} \mu_{ik}]$$

If we substitute this expression for $v_{i,min}^s$ in place of v_i in the expression for entrance location delay (where we use μ_{ij} in place of λ_{ij}^{n+1}), we see that diversion will in fact occur at this minimum metering rate if

$$\ell_{im} \left(\frac{1}{S_a} - \frac{1}{S_f} \right) < \frac{T \sum_{k>m} \mu_{ik}}{1 - \lambda_{i,max} / \sum_{k>m} \mu_{ik}}$$

The required minimum metering rate is then computed by

(1) determination of the largest value of m for which this last inequality holds, and

(2) computation of $v_{i,min}^s$, using this value of m, from the previous equation.

4.3.5 Use of the Metering Design and Evaluation Procedure to Measure Impacts of Freeway Congestion

This section describes how the metering design and evaluation procedure described above can be applied to measure travel times in a "before situation" where no metering is applied.

For our purposes, it is useful to categorize the effects of congestion as

(1) local or non-obstructive queueing,
(2) non-local or obstructive queueing, and
(3) diversion.

These three effects are illustrated in Figure 35. Excess demand on the freeway will lead to congestion manifested as an accumulation of excess vehicles. If this excess is distributed over a "local" region, local in the sense that no upstream exit is obstructed, it is termed local or non-obstructive queueing. If this excess is greater and therefore is distributed over a greater distance including at least one upstream exit, it is termed non-local or

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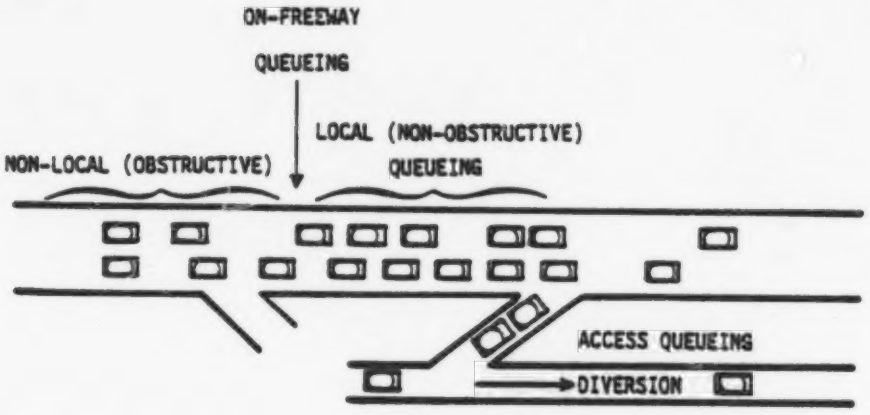

Figure 35. Effects of Congestion

obstructive queueing. The distinction between these two situations relates to the fact that obstructive queueing involves an additional component of delay imposed on vehicles exiting at exits contained with the queue.

Access queueing can also be either local or obstructive. In fact, a crucial aspect of metering design is the accounting for vehicle storage limitations at metering location. Where access queues can be kept within a certain limit, queueing will not obstruct upstream traffic, e.g., street traffic in the vicinity of a metered on-ramp.

The presence of queues introduces an increment of travel time to each vehicle traversing the queue. Where alternate routes are available, a driver may find it advantageous to divert to that alternate, advantageous in the sense of reducing total trip travel time.

The metering design and evaluation procedure (METDSN) is designed to model local, access queueing only. However, it can be used to accurately measure the travel time impacts of local, on-freeway queueing as well. The bases for this use are

(1) restriction of evaluation to local, non-obstructive, on-freeway queueing,
(2) the proportional distribution structure of OD demand volumes, and
(3) no diversion.

The technique for using METDSN is to shift the on-freeway queueing to access queueing, which METDSN accurately measures, as indicated in Figure 36. This technique accurately reflects the travel times associated with on-freeway queueing if

(1) the on-freeway volumes are accurately modeled, and
(2) the queueing delays which would be accrued on the freeway are accurately measured.

In order to shift queueing to access locations, METDSN is used to produce metering rates sufficient to meet freeway capacity constraints. This assumes that all queueing occurs at access locations. Further, the metering rates are unconstrained (i.e., no minimum or maximum rates are associated with metering rates and no maximum entrance volume constraints are imposed). As a result, the only constraints imposed are the freeway capacities.

The (pure) proportional distribution structure of the OD demand volumes means that the composition of the queue that develops at an access location is identical to that which would develop in the on-freeway queue. Taking these observations together, it follows that the modeled freeway volumes and queues coincide with freeway volumes and queues that would exist with local on-freeway queueing. The immediate consequence is that the freeway travel time (less the on-freeway queueing delay) is precisely measured.

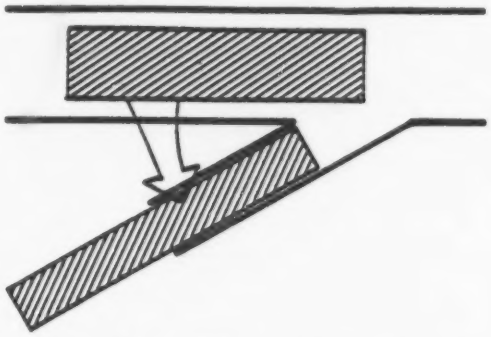

Figure 36. Shift of On-Freeway Queueing to Access Queueing

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Next, we observe that the queueing delay is not affected by moving the queue to the access location. Suppose the capacity at the bottleneck is fixed. Figure 37 illustrates the familiar relationships between demand and capacity. From this, it is obvious that the queue length (number of vehicles) and associated delay is not affected by the location of the queue as long as the volume serviced is not affected.

4.3.6 Example Application of Metering Design and Evaluation Procedure

Due to the need to account for many practical constraints in metering design (freeway capacity, ramp metering limits and queue storage), the modeling of diversion, representation of traffic demand as variable from time slice to time slice, and the need to make many evaluations, a computer program was developed to execute the metering design and evaluation procedure.

Here, we present a simple example application of this program. The traffic situation is that previously diagrammed in Figure 29. Additional input data items are displayed in Table 10. From this, it can be seen that both ramp and mainline metering are being considered. (Under heading "TYPE", "M ON" means a metered entrance.)

The results produced by the program are displayed in Table 11. First, results of each of the two time slices are displayed; next, summaries for the whole control period are displayed. The asterisk under the reading "CAPACITY" indicates that the freeway volume is at capacity at that location. The asterisk under the heading "ON/OFF VOL" indicates that the entrance at this location is metered. It will be noted that the queue storage constraint at Location 2, "ON 1", has forced use of mainline metering in the second time slice.

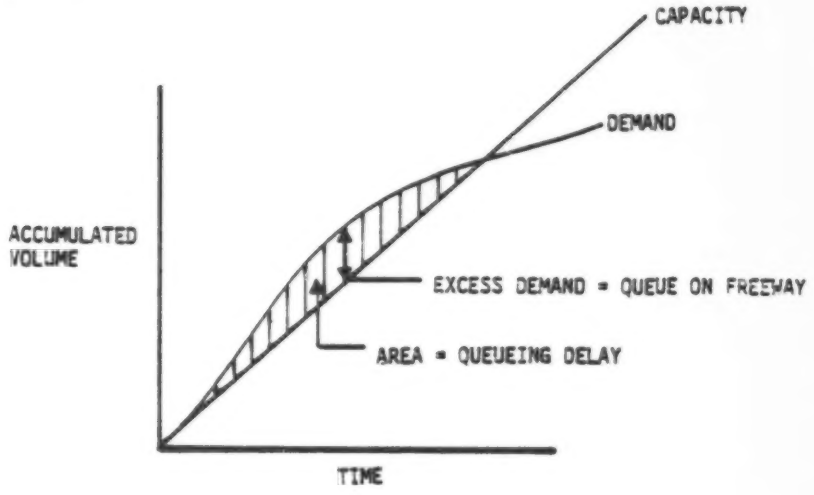

Figure 37. Accumulation of Excess Demand

Table 10. Data Inputs for Example Application of Metering Design and Evaluation Procedure

PROBLEM STRUCTURE INPUT DATA

FREEWAY SPEED (MI/HR): 54.
ALTERNATE ROUTE SPEED (MI/HR): 30.
NUMBER OF SECTIONS: 6
NUMBER OF TIME SLICES: 2
DURATION OF EACH TIME SLICE (MIN): 15.
OD DEMAND VOLUME FILE: TWOTIM.ODE
TOTAL OD VOLUME MULTIPLIER: 1.0500
RAMP CONSTRAINT OPTION (0 NO CONSTRAINT, 1 WITH CONSTRAINT): 1

LOCATION	TYPE	MIN RAMP RATE	MAX RAMP RATE	VOL MAX RATE	QUE MAX (VEH)	FREEWAY CAPACITY	SECTION LENGTH
1 UPSTREAM	M ON	2000.	4000.	4500.	200.	4500.	0.00
2 ON 1	M ON	240.	900.	1500.	50.	4500.	1.00
3 OFF 1	OFF	0.	0.	0.	0.	4500.	0.50
4 ON 2	M ON	360.	1800.	3000.	100.	4500.	0.50
5 OFF 2	OFF	0.	0.	0.	0.	4500.	0.50
6 DWNSTREAM	OFF	0.	0.	0.	0.	4500.	0.75

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Table 11. Results of Example Application of Metering Design and Evaluation Procedure

METERING DESIGN AND EVALUATION FOR TIME SLICE 1

	CAPACITY		PREVOL		ON/OFF VOL	
1 UPSTREAM	4800.		0.	M ON	4800.	*
2 ON 1	4800.		4800.	M ON	300.	*
3 OFF 1	4800.	*	4800.	OFF	-1600.	
4 ON 2	4800.		3400.	M ON	600.	
5 OFF 2	4800.		4800.	OFF	-1600.	
6 DOWNSTREAM	4800.		3975.	OFF	-3975.	

SUMMARY OF METERING PLAN
WITH DIVERSION
TIME SLICE 1 OF 2

ENTRANCE	CLOSURE	DEMAND	METERING LIMITS MIN	MAX	VOLUME	ENTVOL	INTRANT	DIVERT	DELAY	HEADWAY
1 UPSTREAM	0.00	4800.	3600.	4800.	4800.	4800.	0.	0.	0.00	0.00
2 ON 1	0.00	300.	240.	300.	1200.	300.	300.	11.	0.02	48.00
4 ON 2	0.00	600.	300.	1800.	3600.	600.	0.	0.	0.00	0.00

ALL MEASURES IN VEHICLE-HOURS

RAMP DELAY	0.02
FREEWAY TRAVEL TIME:	97.97
ALTERNATE ROUTE TRAVEL TIME:	0.00
TOTAL TRAVEL TIME :	84.18

METERING DESIGN AND EVALUATION FOR TIME SLICE 2

	CAPACITY		PREVOL		ON/OFF VOL	
1 UPSTREAM	4800.		0.	M ON	4800.	*
2 ON 1	4800.		4800.	M ON	300.	*
3 OFF 1	4800.	*	4800.	OFF	-1600.	
4 ON 2	4800.		3200.	M ON	681.	
5 OFF 2	4800.		4482.	OFF	-1600.	
6 DOWNSTREAM	4800.		3182.	OFF	-3182.	

SUMMARY OF METERING PLAN
WITH DIVERSION
TIME SLICE 2 OF 2

ENTRANCE	CLOSURE	DEMAND	METERING LIMITS MIN	MAX	VOLUME	ENTVOL	INTRANT	DIVERT	DELAY	HEADWAY
1 UPSTREAM	0.00	4418.	3600.	4800.	4800.	4800.	0.	0.	12.81	108.00
2 ON 1	40.00	681.	240.	300.	1200.	300.	300.	9.	11.78	48.10
4 ON 2	0.00	681.	300.	1800.	3600.	681.	0.	0.	0.00	0.00

ALL MEASURES IN VEHICLE-HOURS

RAMP DELAY	24.57
FREEWAY TRAVEL TIME:	97.03
ALTERNATE ROUTE TRAVEL TIME:	0.44
TOTAL TRAVEL TIME :	82.04

SUMMARY OF METERING PLAN
WITH DIVERSION

TIME SLICE		ENTRANCE LOCATION 1 UPSTREAM	2 ON 1	4 ON 2
1	METERING RATE	0.	300.	0.
	QUEUED VEH	0.	48.	0.
	DIVERTED VEH	0.	11.	0.
2	METERING RATE	4800.	300.	0.
	QUEUED VEH	182.	40.	0.
	DIVERTED VEH	0.	9.	0.

SUMMARY OF PERFORMANCE MEASURES FOR CONTROL PERIOD
ALL MEASURES IN VEHICLE-HOURS

RAMP DELAY:	39.39
FREEWAY TRAVEL TIME:	118.60
ALTERNATE ROUTE TRAVEL TIME:	1.60
TOTAL TRAVEL TIME:	140.79

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5.0 EVALUATION RESULTS

The guidelines presented in Section 2 were based in part upon the quantitative results obtained by application of the evaluation procedures, described in Section 4, to a set of representative traffic situations. The purpose of this effort was to identify those features of traffic situations which influenced the suitability of implementing mainline and connector metering.

The metering evaluation effort involved application of the evaluation procedures to five sites. These sites were amongst those visited as described in Section 3. The site visits provided detailed geometric and traffic demand volume data necessary for application of the evaluation procedures.

The analysis approach involved examination of each of these five sites with variations in:

- Metering structure: No metering, ramp metering only, mainline metering only, ramp and connector metering, ramp and mainline metering, and ramp, connector and mainline metering (as appropriate to each site).
- Traffic demand: The nominal traffic demand data identified in each site visit was varied by scaling all demands by a common factor.
- Quality of alternate route: Three levels of alternate route speed were considered, representing poor, good and excellent alternate routes.

In the next section, the five sites and their characteristics are identified. The analyses undertaken for each site are described in greater detail in Section 5.2. Section 5.3 presents detailed, quantitative evaluation results for each of the five sites. Section 5.4 presents general conclusions drawn from the detailed evaluation results.

5.1 Characteristics of Sites Evaluated

The five sites studied were:

- Route 94, westbound in San Diego (AM Peak)
- I-10, eastbound in Los Angeles (AM Peak)
- I-35W, southbound in Minneapolis (PM Peak)
- Route 59 (Southwest Freeway), inbound in Houston (AM Peak)
- I-395 (Shirley Highway), inbound in Virginia (AM Peak)

The general locations of these sites are identified in Section 3.

Figures 38 through 42 present the gross geometric characteristics of each of these sites. The first four sites all involve actual or candidate connector metering. Mainline metering was considered in the second, fourth and fifth sites.

5.2 Analysis Approach

A common approach to the analysis of connector and/or mainline metering for each site was adopted:

(1) OD Demand Data Estimation

The control period was partitioned into time slices of 15-minute durations. The number of time slices varied from eight to fifteen over the five sites. Entrance/exit volume data were used in the origin-destination demand volume estimation procedure to establish OD demand data for each time slice. This demand is termed the "nominal" demand. For each site, except I-395 (Shirley Highway), entrance/exit volume data were available by time slice. In the case of the I-395 site, volume data were available for a peak time slice. A peak period demand profile was generated by using overall scale factors of .8, .8, 1.0, 1.0, .8, .8, .7, and .6 for the eight time slices.

In order to eliminate an undesirable "end-effect", each freeway segment was extended by adding four 1-mile sections, with an exit at each node. One quarter of the volume leaving the segment was assigned to each of these four exits. This device has the effect of representing the extension of trips beyond the end of the segment studied for metering and results in more realistic modeling of diversion.

(2) Determination of Critical Demand Volumes

Demand volume variations are defined by applying a common scale factor to the "nominal" OD demand volume data. Critical demand volumes (i.e., critical scale factors) were determined for each site such that a form of metering was just able to handle the demand, i.e., prevent freeway congestion while satisfying metering rate and queue storage constraints. Critical values were determined for

- no metering
- ramp metering only
- mainline metering only (I-395 only)
- ramp and connector metering (all except I-395)
- ramp and mainline metering
- ramp, connector and mainline metering (all except I-395).

For a given site, the critical value is least for no metering, and generally increased as the options were considered in the order indicated.

(3) No Metering Freeway Congestion Impact

For values of demand above critical for no metering, freeway congestion will

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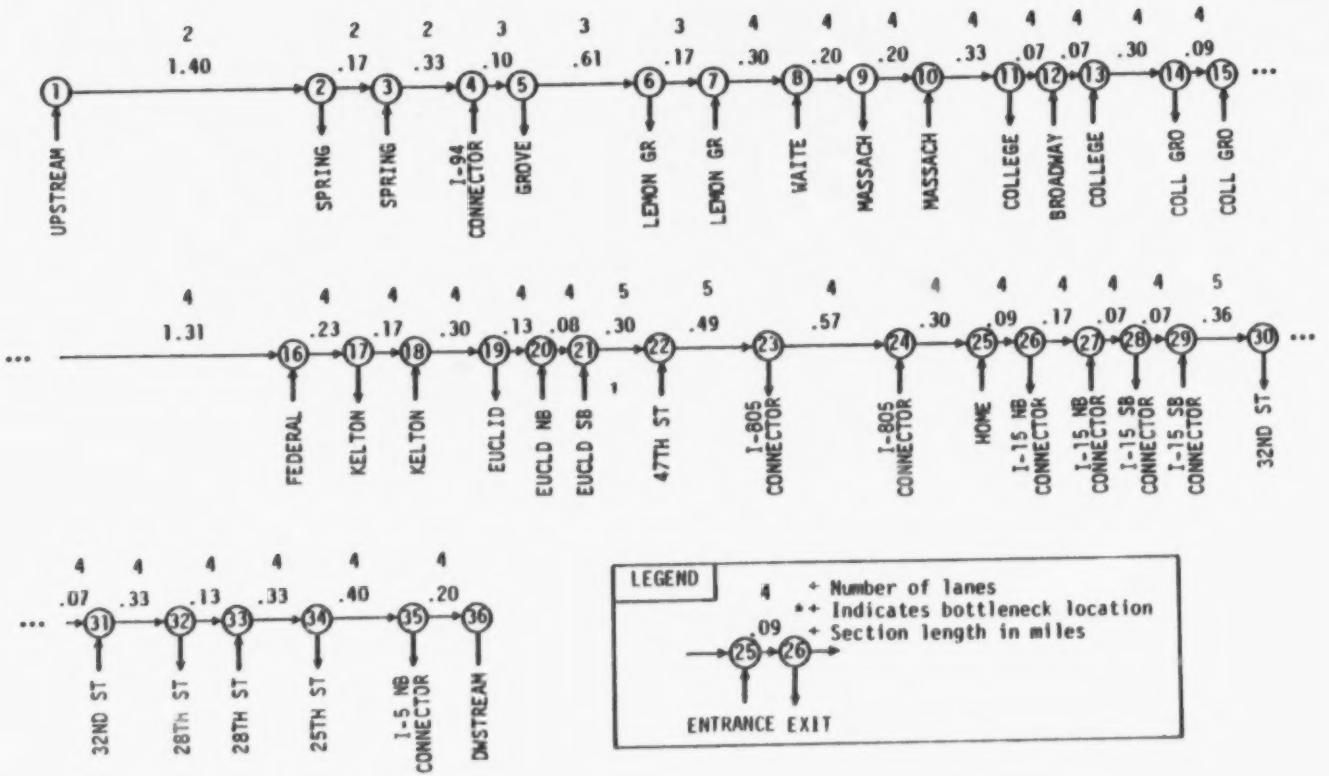

Figure 38. Network Representation of Route 94, Westbound Site in San Diego

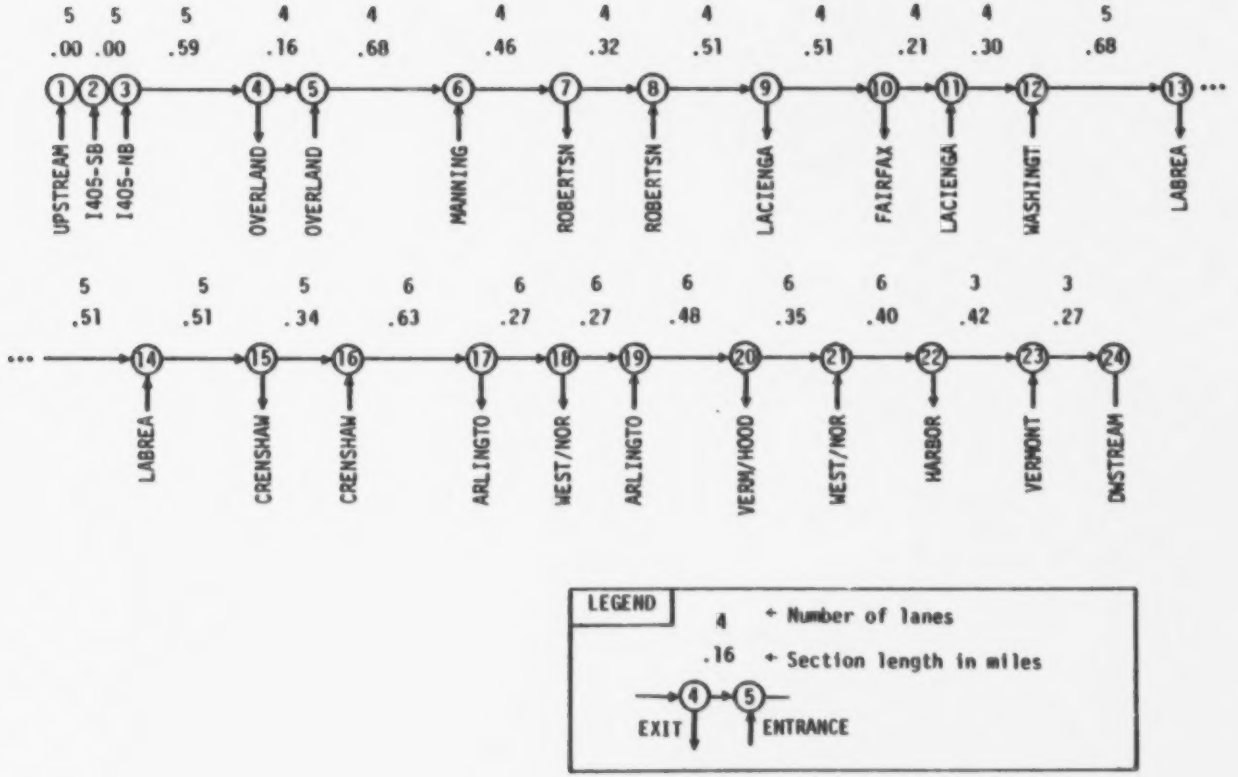

Figure 39. Network Representation of I-10, Eastbound Site in Los Angeles

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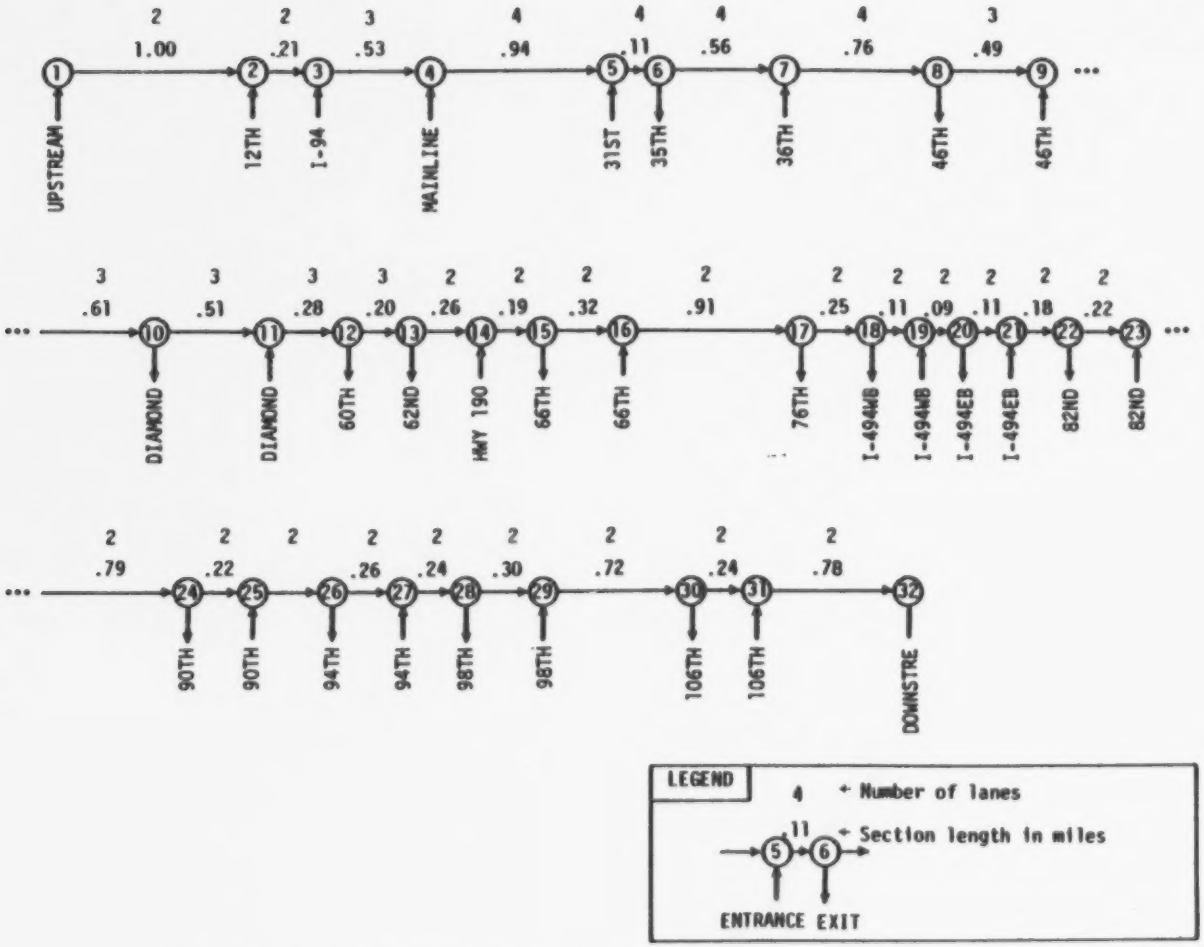

Figure 40. Network Representation of I-35W, Southbound Site in Minneapolis

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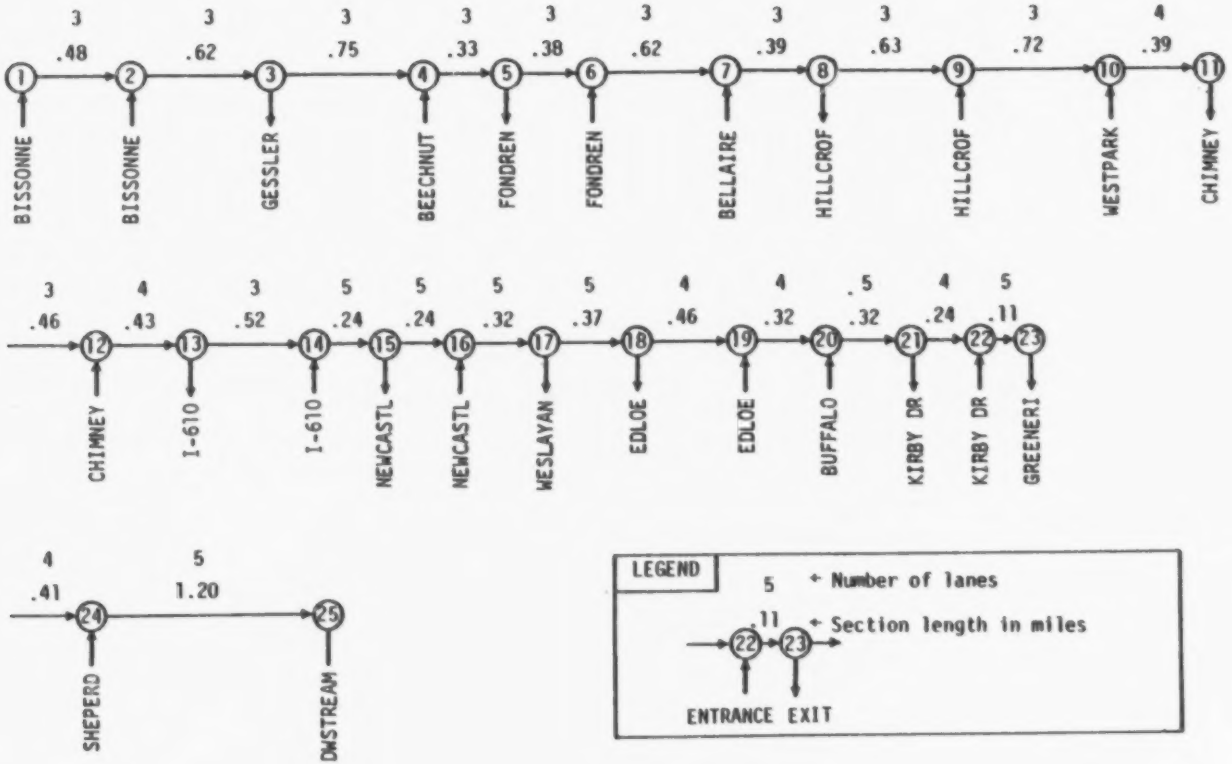

Figure 41. Network Representation of Route 59 (Southwest Freeway), Inbound Site in Houston

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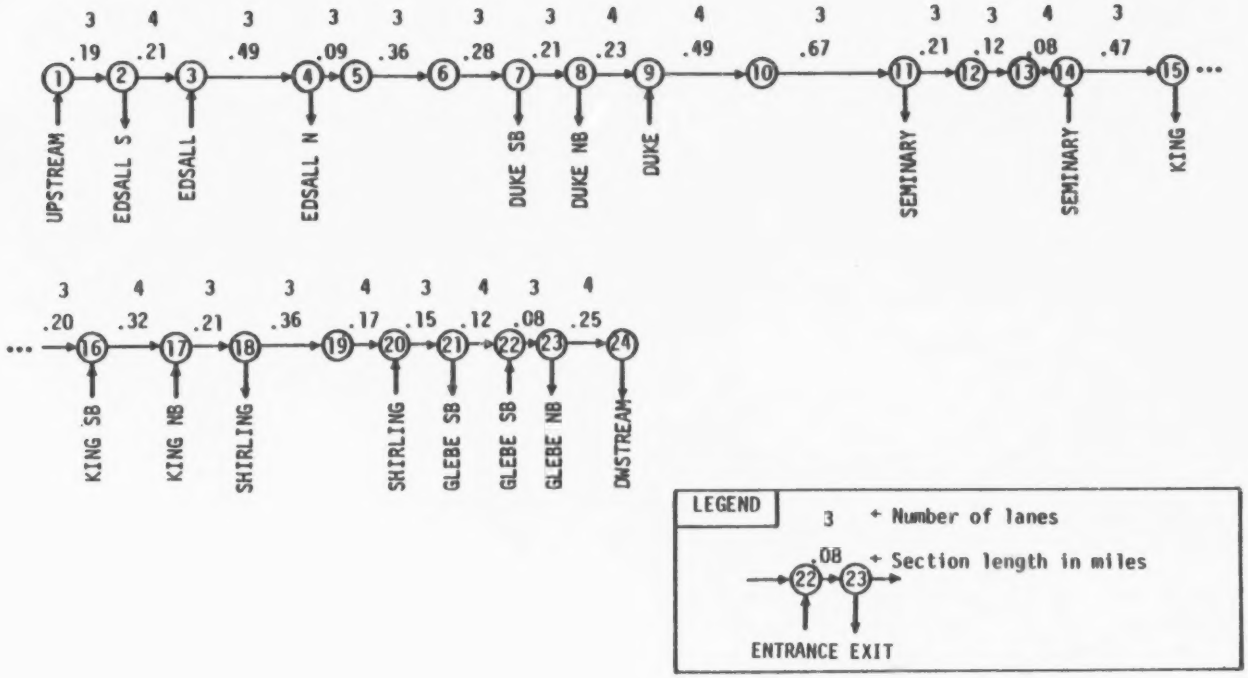

Figure 42. Network Representation of I-395 (Shirley Highway), Inbound in Virginia

occur. The technique described in Section 4.3.5 for using the metering design and evaluation procedure to measure localized freeway congestion was applied across the full range of traffic demand considered for the various metering alternatives for each site.

(4) Metering Design and Evaluation

Metering designs and travel time evaluations were made for each form of metering, for a range of demand volumes from the critical value of no metering through the critical value for that form of metering, and for three values of alternate route speed: 10 miles per hour (a "poor" alternate), 25 miles per hour (a "good" alternate) and 40 miles per hour (an "excellent" alternate). Total travel time measures were compared with the no metering travel time results to obtain relative changes.

5.3 Site-Specific Evaluation Results

The results of applying the procedure described in Section 5.2 are tabulated in Tables 12 through 16.

By scanning these tables, two general features are easily observed:

(1) The use of connector and/or mainline metering extends the range of demand volumes that can be handled, i.e., metering plans exist for greater volumes which remove congestion from the freeway and which satisfy metering rate and queue storage constraints.

(2) The quality of the alternate route has very significant effects upon the range of demand volumes that can be handled, and, at a fixed level of demand, upon the benefit of metering. With poor alternates (alternate route speed of 10 miles per hour), changes from no metering are very small, and in some cases represent increases in total travel time. With good alternates (alternate route speed of 25 miles per hour), changes from no metering are moderate and are generally beneficial. With excellent alternates (alternate route speed of 40 miles per hour), changes from no metering are moderately to very substantially beneficial.

In the instance of the Rte 94 site in San Diego (see Table 12), the addition of connector metering to ramp metering accommodates 3 to 4 percent more traffic, and results in travel time benefits in all cases. The addition of mainline metering to ramp metering, however, is generally not effective. The combination of ramp, connector and mainline metering is effective where ramp and connector metering alone cannot handle the demand.

In the instance of the I-10 site in Los Angeles (see Table 13), all forms of metering yield disbenefits where the alternate is poor, or even of moderate quality. In this instance, we examined the impact of increased queue storage with a moderate quality alternate. This might result, for example, by providing for (or accounting for) queue storage on street links approaching an on ramp. The increased storage was related to on ramps only and amounted to no change at certain ramps up to 37 vehicles at one on ramp. The impacts are seen to be small, but generally provide benefits in travel time and volume level that can be handled. With an excellent alternate, moderate to substantial benefits arise. Connector metering substantially extends the demand volumes which can be handled. Mainline metering is nearly equivalent to connector metering (at this site, they occur at the same location). The combination of ramp, connector and mainline metering handles the greatest demand volume with very substantial benefit.

Results for the third site, I-35W in Minneapolis, are presented in Table 14. In this instance, the impact of connector metering is striking, largely because the connector demands are very large. Ramp metering alone has a severely limited ability to handle increases in traffic demand, because of the uncontrolled connector demand. With the use of connector metering, benefits are moderate to substantial with a good alternate and large where there is an excellent alternate. Mainline metering is a somewhat less effective alternative to connector metering.

Results for the Route 59 (Southwest Freeway) site in Houston are presented in Table 15. Travel time impacts are negligible where the alternate route is poor. Moderate benefits arise with a good alternate and very substantial benefits result with an excellent alternate route. In all but the most extreme traffic demand case, and then only with a good or excellent alternate, metering of the connector is not used. This occurs because the connectors are located downstream of the bottleneck. Mainline metering can be seen to substantially extend the range of traffic demand which can be handled and results in moderate to substantial travel time benefits with good and excellent alternates, respectively. Mainline metering has been suggested as a supplement to the existing ramp metering implementation at this site. If a reasonable alternate can be provided, this should be beneficial.

Table 16 presents results for I-395 (Shirley Highway), inbound in Virginia. In this instance, there is no connector, so the options examined were ramp and/or mainline metering. Mainline metering alone is not particularly effective. It would relieve only a small amount of freeway congestion and, for a poor or moderate quality alternate, results in travel time disbenefits. The alternate for

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Table 12. Metering Design and Evaluation Results for I-94, Westbound in San Diego
(All Measures in Vehicle-Hours)

VOLUME (% OF NOMINAL)

	97	100	101	102	104	105	106	108	111	
NO METERING	0 2565 0 2565	35 2645 0 2680	84 2671 0 2755	143 2698 0 2841	288 2750 0 3038	401 2777 0 3178	536 2803 0 3339	845 2856 0 3701	1388 2936 0 4324	
ALTERNATE ROUTE SPEED: 10 miles per hour										
RAMP METERING	Metering Not Required	37 2645 0 2682 +.1%			FREEWAY	CONGESTED				
RAMP AND CONNECTOR METERING		31 2645 0 2676 -.1%	72 2671 1 2743 -.4%	126 2697 2 2825 -.6%	252 2749 6 3008 -1.0%		FREEWAY	CONGESTED		
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	97 2671 1 2769 +.5%			FREEWAY	CONGESTED			
RAMP, CONNECTOR, AND MAINLINE METERING		Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering		FREEWAY	CONGESTED		

Key to Table:

37	Entrance Location Delay
2645	Freeway Travel Time
0	Alternate Route Travel Time
2682	Total Travel Time
+.1%	Change in Total Travel Time from No Metering

Table 12. Metering Design and Evaluation Results for I-94, Westbound in San Diego (All Measures in Vehicle-Hours) (Continued)

	VOLUME (% OF NOMINAL)									
	97	100	101	102	104	105	106	108	111	
ALTERNATE ROUTE SPEED: 25 miles per hour										
RAMP METERING	Metering Not Required	8 2642 3 2653 -1.0%	17 2667 5 2690 -2.4%			Freeway	Congested			
RAMP AND CONNECTOR METERING		23 2644 1 2668 - .4%	54 2670 2 2726 -1.1%	101 2696 3 2800 -1.4%	161 2744 14 2918 -3.9%		Freeway	Congested		
RAMP AND MAINLINE METERING		25 2644 1 2671 - .3%	68 2670 2 2740 - .5%	141 2696 3 2841 no change			Freeway	Congested		
RAMP, CONNECTOR, AND MAINLINE METERING		Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	225 2966 23 3014 -5.2%	292 2790 30 3112 -6.8%	Freeway	Congested	

Key to Table:

37	Entrance Location Delay
2645	Freeway Travel Time
0	Alternate Route Travel Time
2682	Total Travel Time
+.1%	Change in Total Travel Time from No Metering

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Table 12. Metering Design and Evaluation Results for I-94, Westbound in San Diego (All Measures in Vehicle-Hours) (Concluded)

	VOLUME (% OF NOMINAL)									
	97	100	101	102	104	105	106	108	111	
ALTERNATE ROUTE SPEED: 40 miles per hour										
RAMP METERING	Metering Not Required	8 2642 3 2653 -1.0%	17 2667 5 2690 -2.4%	25 2690 10 2725 -4.1%	60 2735 21 2816 -7.3%	82 2755 29 2867 -9.8%	64 2773 40 2878 -13.8%	Freeway	Congested	
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	Connector not used, same as ramp metering	Connector not used, same as ramp metering	42 2734 22 2798 -7.9%	83 2757 26 2867 -9.8%	115 2778 34 2927 -12.3%	124 2817 53 2994 -19.1%	Freeway Congested	
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	112 2808 66 2965 -19.3%	Freeway Congested	
RAMP, CONNECTOR, AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	240 2878 78 3196 -26.1%	

Key to Table:

37	Entrance Location Delay
2645	Freeway Travel Time
0	Alternate Route Travel Time
2682	Total Travel Time
+.1%	Change in Total Travel Time from No Metering

Table 13. Metering Design and Evaluation Results for I-10, Eastbound in Los Angeles
(All Measures in Vehicle-Hours)

	VOLUME (% OF NOMINAL)									
	89	97	99	101	102	103	104	105	109	113
NO METERING	0 3285 0 3285	101 3580 0 3681	173 3653 0 3827	269 3727 0 3997	353 3764 0 4117	444 3801 0 4245	536 3838 0 4374	650 3875 0 4526	1267 4023 0 5289	2305 4170 0 6475
ALTERNATE ROUTE SPEED: 10 miles per hour										
RAMP METERING	Metering Not Required	118 3580 0 3698 +.5%				Freeway	Congested			
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	227 3653 0 3882 +1.4%	377 3727 3 4106 +2.7%	483 3763 6 4253 +3.3%			Freeway	Congested	
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	229 3654 0 3883 +1.4%	386 3727 1 4114 +2.9%			Freeway	Congested		
RAMP, CONNECTOR, AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	645 3799 10 4454 +4.9%		Freeway	Congested	

Key to Table:

118	Entrance Location Delay
3580	Freeway Travel Time
0	Alternate Route Travel Time
3698	Total Travel Time
+.5%	Change in Total Travel Time from No Metering

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Table 13. Metering Design and Evaluation Results for I-10, Eastbound in Los Angeles (All Measures in Vehicle-Hours) (Continued)

	VOLUME (% OF NOMINAL)									
	89	97	99	101	102	103	104	105	109	113
ALTERNATE ROUTE SPEED: 25 miles per hour										
RAMP METERING	Metering Not Required	99 3579 2 3680 no change				Freeway	Congested			
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	172 3651 5 3828 no change	292 3724 8 4024 + .7%	387 3759 10 4157 +1.0%	475 3792 21 4287 +1.0%		Freeway	Congested	
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	172 3651 4 3828 no change	297 3725 6 4027 + .7%	393 3760 9 4161 +1.0%		Freeway	Congested		
RAMP, CONNECTOR, AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	603 3823 34 4459 +1.9%		Freeway	Congested

Key to Table:

118	Entrance Location Delay
3580	Freeway Travel Time
0	Alternate Route Travel Time
3698	Total Travel Time
+.5%	Change in Total Travel Time from No Metering

Table 13. Metering Design and Evaluation Results for I-10, Eastbound in Los Angeles
(All Measures in Vehicle-Hours) (Continued)

	VOLUME (% OF NOMINAL)									
	89	97	99	101	102	103	104	105	109	113
ALTERNATE ROUTE SPEED: 25 miles per hour (increased queue storage)										
RAMP METERING	Metering Not Required	96 3579 2 3677 - .1%	167 3651 5 3823 - .1%			Freeway	Congested			
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	Connector not used, same as ramp metering	284 3724 7 4015 + .5%	372 3760 10 4142 + .9%	474 3794 15 4283 + .9%	589 3825 29 4443 +1.6%	Freeway	Congested	
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	284 3724 7 4015 + .5%	376 3760 9 4145 + .9%	479 3795 14 4288 +1.0%		Freeway	Congested	
RAMP, CONNECTOR AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	731 3857 38 4626 +2.2%		

Key to Table:

118	Entrance Location Delay
3580	Freeway Travel Time
0	Alternate Route Travel Time
3698	Total Travel Time
+.5%	Change in Total Travel Time from No Metering

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Table 13. Metering Design and Evaluation Results for I-10, Eastbound in Los Angeles
(All Measures in Vehicle-Hours) (Concluded)

	VOLUME (% OF NOMINAL)									
	89	97	99	101	102	103	104	105	109	113
ALTERNATE ROUTE SPEED: 40 miles per hour										
RAMP METERING	Metering Not Required	48 3570 14 3632 -1.3%	91 3640 18 3749 -2.0%	———	———	——— Freeway	Congested ———	———	———	———
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	Connector not used, same as ramp metering	121 3702 35 3857 -3.5%	140 3730 47 3916 -4.9%	189 3763 52 4004 -5.7%	228 3794 60 4081 -6.7%	255 3820 74 4150 -8.3%	359 3918 141 4419 -16.4%	Freeway Congested
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	122 3702 34 3859 -3.5%	156 3732 44 3931 -4.5%	195 3764 50 4009 -5.6%	228 3794 59 4081 -6.7%	256 3820 74 4150 -8.3%	——— Freeway	Congested ———
RAMP, CONNECTOR, AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	497 3992 241 4729 -27.0%

Key to Table:

118	Entrance Location Delay
3580	Freeway Travel Time
0	Alternate Route Travel Time
3698	Total Travel Time
+.5%	Change in Total Travel Time from No Metering

Table 14. Metering Design and Evaluation Results for I-35W, Southbound in Minneapolis
(All Measures in Vehicle-Hours)

	VOLUME (% OF NOMINAL)									
	68	71	74	75	77	78	84	85	92	93
	0 3090 0 3090	10 3226 0 3236	82 3363 0 3445	141 3408 0 3549	311 3499 0 3810	427 3544 0 3971	1935 3817 0 5752	2302 3862 0 6165	5539 4090 0 9629	6041 4119 0 10160
ALTERNATE ROUTE SPEED: 10 miles per hour										
RAMP METERING	Metering Not Required	22 3226 0 3248 +.4%				Freeway	Congested			
RAMP AND CONNECTOR METERING		10 3226 0 3236 no change	76 3362 3 3441 -.1%	131 3407 5 3543 -.2%	302 3497 11 3810 no change		Freeway	Congested		
RAMP AND MAINLINE METERING		21 3226 0 3248 +.4%	144 3362 2 3509 +1.9%	268 3407 6 3680 +3.7%			Freeway	Congested		
RAMP, CONNECTOR, AND MAINLINE METERING		Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	304 3497 10 3811 no change	475 3542 14 4031 +1.5%		Freeway	Congested	

Key to Table:

22	Entrance Location Delay
3226	Freeway Travel Time
0	Alternate Route Travel Time
3248	Total Travel Time
+.4%	Change in Total Travel Time from No Metering

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Table 14. Metering Design and Evaluation Results for I-35W, Southbound in Minneapolis
(All Measures in Vehicle-Hours) (Continued)

	VOLUME (% OF NOMINAL)									
	68	71	74	75	77	78	84	85	92	93
ALTERNATE ROUTE SPEED: 25 miles per hour										
RAMP METERING	Metering Not Required	21 3226 0 3247 +.3%				Freeway	Congested			
RAMP AND CONNECTOR METERING		8 3226 0 3234 -.1%	41 3359 8 3408 -1.1%	50 3401 15 3466 -2.3%	120 3486 28 3634 -4.6%	143 3525 42 3710 -6.6%	337 3729 190 4256 -26.0%			
RAMP AND MAINLINE METERING		19 3226 0 3246 +.3%	108 3359 7 3474 +.8%	187 3401 15 3603 +1.5%	416 3474 55 3945 +3.5%	457 3485 129 4070 +2.5%		Freeway	Congested	
RAMP, CONNECTOR, AND MAINLINE METERING		Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	352 3733 180 4266 -25.8%	707 3777 185 4669 -24.3%	Freeway	Congested

Key to Table:

22	Entrance Location Delay
3226	Freeway Travel Time
0	Alternate Route Travel Time
3248	Total Travel Time
+.4%	Change in Total Travel Time from No Metering

Table 14. Metering Design and Evaluation Results for I-35W, Southbound in Minneapolis
(All Measures in Vehicle-Hours) (Concluded)

	VOLUME (% OF NOMINAL)									
	68	71	74	75	77	78	84	85	92	93
ALTERNATE ROUTE SPEED: 40 miles per hour										
RAMP METERING	Metering Not Required	15 3224 2 3242 +.2%	53 3344 25 3422 -.7%	88 3375 45 3508 -1.2%			Freeway	Congested		
RAMP AND CONNECTOR METERING		6 3225 1 3232 -.1%	13 3355 11 3378 -1.9%	25 3398 14 3437 -3.2%	56 3479 27 3567 -6.5%	53 3514 41 3608 -9.1%	207 3719 132 4058 -29.5%	228 3749 153 4131 -33.0%	526 3894 387 4807 -50.1%	
RAMP AND MAINLINE METERING		16 3225 1 3243 +.2%	67 3351 16 3434 -.3%	105 3385 31 3522 -.8%	198 3431 92 3720 -2.4%	215 3445 133 3794 -4.5%	356 3505 421 4282 -25.6%	355 3509 477 4342 -29.6%	543 3520 891 4954 -48.6%	611 3512 964 50P7 -49.5%
RAMP, CONNECTOR, AND MAINLINE METERING		Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	Mainline not used, same as ramp and connector metering	216 3724 126 4066 -29.3%	246 3755 145 4146 -32.7%	672 3874 413 4959 -48.5%	708 3884 461 5054 -50.3%

Key to Table:

22	Entrance Location Delay
3226	Freeway Travel Time
0	Alternate Route Travel Time
3248	Total Travel Time
+.4%	Change in Total Travel Time from No Metering

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Table 15. Metering Design and Evaluation Results for Route 59 (Southwest Freeway), Inbound in Houston

	VOLUME (% OF NOMINAL)									
	79	85	86	92	93	100	101	102	111	120
NO METERING	0 4008 0 4008	159 4313 0 4472	208 4363 0 4571	607 4668 0 5275	711 4719 0 5429	1794 5074 0 6858	2030 5124 0 7155	2268 5175 0 7443	6025 5546 0 11571	10982 5754 0 16736
ALTERNATE ROUTE SPEED: 10 miles per hour										
RAMP METERING	Metering Not Required	154 4312 1 4468 -.1%	205 4363 1 4570 no change			Freeway	Congested			
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	Connector not used, same as ramp metering			Freeway	Congested			
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	665 4664 20 5349 +1.4%	782 4714 23 5519 +1.7%		Freeway	Congested		
RAMP, CONNECTOR, AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector not used, same as ramp and mainline metering	Connector not used, same as ramp and mainline metering		Freeway	Congested		

Key to Table:

154	Entrance Location Delay
4312	Freeway Travel Time
1	Alternate Route Travel Time
4468	Total Travel Time
-.1%	Change in Total Travel Time from No Metering

Table 15. Metering Design and Evaluation Results for Route 59 (Southwest Freeway), Inbound in Houston (Continued)

VOLUME (% OF NOMINAL)

	79	85	86	92	93	100	101	102	111	120
ALTERNATE ROUTE SPEED: 25 miles per hour										
RAMP METERING	Metering Not Required	63 4307 12 4382 -2.0%	76 4356 17 4449 -2.7%	235 4645 49 4929 -6.6%			Freeway	Congested		
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	Connector not used, same as ramp metering	Connector not used, same as ramp metering			Freeway	Congested		
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	289 4695 52 5035 -7.3%	1031 4994 173 6198 -9.8%		Freeway	Congested	
RAMP, CONNECTOR, AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector not used, same as ramp and mainline metering	939 5005 149 6093 -11.3%	1090 5043 177 6309 -11.8%	1286 5066 236 6588 -11.5%	Freeway	Congested

Key to Table:

154	Entrance Location Delay
4312	Freeway Travel Time
1	Alternate Route Travel Time
4468	Total Travel Time
-.1%	Change in Total Travel Time from No Metering

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Table 15. Metering Design and Evaluation Results for Route 59 (Southwest Freeway), Inbound in Houston (Concluded)

	VOLUME (% OF NOMINAL)									
	79	85	86	92	93	100	101	102	111	120
ALTERNATE ROUTE SPEED: 40 miles per hour										
RAMP METERING	Metering Not Required	32 4301 15 4349 -2.7%	41 4349 20 4410 -3.5%	90 4624 59 4773 -9.5%	93 4668 68 4829 -11.0%	194 4963 150 5306 -22.7%	231 5001 167 5399 -24.5%	Freeway	Congested	
RAMP AND CONNECTOR METERING		Connector not used, same as ramp metering	Connector not used, same as ramp metering	Connector not used, same as ramp metering	Connector not used, same as ramp metering	Connector not used, same as ramp metering	Connector not used, same as ramp metering	Freeway	Congested	
RAMP AND MAINLINE METERING		Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	275 5037 186 5499 -26.1%	858 5275 482 6615 -42.8%	Freeway Congested
RAMP, CONNECTOR, AND MAINLINE METERING		Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	Connector and mainline not used, same as ramp metering	299 5044 177 5520 -25.8%	742 5338 397 6477 -44.0%	1279 5480 818 7577 -54.7%

Key to Table:

154	Entrance Location Delay
4312	Freeway Travel Time
1	Alternate Route Travel Time
4468	Total Travel Time
-.1%	Change in Total Travel Time from No Metering

Table 16. Metering Design and Evaluation Results for I-395 (Shirley Highway), Inbound in Virginia (All Measures in Vehicle-Hours)

	VOLUME (% OF NOMINAL)							
	90	93	94	97	98	105	107	118
NO METERING	0 1314 0 1314	36 1358 0 1393	48 1372 0 1420	105 1416 0 1521	135 1431 0 1566	451 1533 0 1984	606 1562 0 2168	1891 1673 0 3564
ALTERNATE ROUTE SPEED: 10 miles per hour								
RAMP METERING	Metering Not Required	32 1357 1 1390 -0.2%	45 1372 1 1418 -0.1%	89 1415 4 1508 -0.9%	110 1429 8 1546 -1.2%	Freeway	Congested	
MAINLINE METERING	Metering Not Required	76 1357 0 1434 +2.9%			Freeway	Congested		
RAMP AND MAINLINE METERING	Metering Not Required	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	395 1527 31 1953 -1.6%	Freeway	Congested

Key to Table:

32	Entrance Location Delay
1357	Freeway Travel Time
1	Alternate Route Travel Time
1390	Total Travel Time
-0.2%	Change in Total Travel Time from No Metering

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Table 16. Metering Design and Evaluation Results for I-395 (Shirley Highway), Inbound in Virginia (All Measures in Vehicle-Hours) (Continued)

VOLUME (% OF NOMINAL)

	90	93	94	97	98	105	107	118
ALTERNATE ROUTE SPEED: 25 miles per hour								
RAMP METERING	Metering Not Required	26 1356 3 1385 -0.6%	34 1370 4 1409 -0.8%	54 1410 14 1477 -2.9%	64 1423 16 1503 -4.0%	Freeway	Congested	
MAINLINE METERING	Metering Not Required	70 1357 1 1428 +2.5%	83 1370 4 1457 +2.6%		Freeway	Congested		
RAMP AND MAINLINE METERING	Metering Not Required	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	213 1517 35 1764 -11.1%	250 1538 52 1839 -15.2%	Freeway Congested

Key to Table:

32	Entrance Location Delay
1357	Freeway Travel Time
1	Alternate Route Travel Time
1390	Total Travel Time
-0.2%	Change in Total Travel Time from No Metering

Table 16. Metering Design and Evaluation Results, for I-395 (Shirley Highway), Inbound in Virginia (All Measures in Vehicle-Hours) (Concluded)

	VOLUME (% OF NOMINAL)							
	90	93	94	97	98	105	107	118
ALTERNATE ROUTE SPEED: 40 miles per hour								
RAMP METERING	Metering Not Required	14 1356 3 1372 -1.5%	19 1369 4 1392 -2.0%	38 1408 10 1456 -4.3%	40 1420 14 1475 -5.8%	Freeway	Congested	
MAINLINE METERING	Metering Not Required	45 1354 5 1404 -0.8%	56 1366 9 1431 +0.8%	86 1400 21 1508 -0.9%		Freeway	Congested	
RAMP AND MAINLINE METERING	Metering Not Required	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	Mainline not used, same as ramp metering	110 1508 33 1651 -16.8%	126 1531 42 1699 -21.6%	341 1629 127 2097 -41.2%

Key to Table:

32	Entrance Location Delay
1357	Freeway Travel Time
1	Alternate Route Travel Time
1390	Total Travel Time
-0.2%	Change in Total Travel Time from No Metering

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this site is in fact quite poor. Ramp metering alone would relieve a somewhat larger amount of freeway congestion, with slight to moderate travel time benefits, depending upon the quality of the alternate. The most effective option is ramp and mainline metering. Substantially more traffic demand can be handled, and travel time benefits range from slight to very substantial. Noting that the alternate for this site is in fact quite poor, the best option, ramp and mainline metering, would be expected to produce only slight benefits.

5.4 Conclusions

In interpreting the evaluation results presented in the preceding tables, it must be kept in mind that the "no metering" results account for delay due to "local freeway congestion" only. Where the delay indicated for "no metering" is small relative to the freeway travel time, it is reasonable to expect that congestion is in fact localized, so that the measures produced are good indicators of actual delay. However, where the indicated delay is a large fraction of the freeway travel time, "obstructive queueing" is likely to actually occur, so that the indicated delay will underestimate actual delay. The larger the delay in relation to freeway travel time, the greater the actual amount of "obstructive queueing". Generally, the net effect of this situation is that cases for which at least moderate travel time benefits are indicated will in actuality produce greater benefits.

The quality of the alternate route can be seen to have a major effect on the efficacy of any metering structure for all five sites. Generally, where the alternate is poor, there is a very limited capability to relieve freeway congestion (i.e., handle traffic demands above that level for which metering is not required). And in this instance, travel time impacts are generally very small (less than 3 percent) and in some cases represent disbenefits. Where the alternate is good, metering is more effective, being able to accommodate larger traffic demands and producing moderate travel time benefits. Where the alternate is excellent, metering is very effective, being able to accommodate large increments in traffic demand and producing substantial to very substantial travel time benefits.

Ramp metering alone, where it is sufficient to handle the traffic demand, generally provides the best result. The principal benefit of adding connector and/or mainline metering to a ramp metering system is to increase the available storage of excess traffic demand. This will be most effective where (1) the connector has a large volume (mainlines almost always do), and (2) the connector and/or mainline metering location is upstream of, but still close to, the bottleneck location. Metering of low volume connectors is generally not effective because: (1) they are often of a geometric design which allows for little storage, and (2) the low demand provides only a limited ability to alleviate the bottleneck. Metering of connectors (and ramps) downstream of the bottleneck cannot relieve the bottleneck. And if the connector and/or mainline is a great distance upstream of the bottleneck, only a fraction of the stored vehicles are in fact destined for the bottleneck, the remainder having destinations at exits upstream of the bottleneck. Metering in such instances could as a result produce travel time disbenefits.

The rationale for adding connector metering in fact depends upon a variation of this last argument. Results for I-35W in Minneapolis provide an excellent example of the point to be made here. Figure 40 previously presented indicates the location of the I-494 EB and WB connectors; the I-494 EB connector has a high volume. From Table 14, and specifically for results pertaining to "alternate route speed 25 miles per hour", it can be seen that ramp metering alone is ineffectual. This occurs, because, in the absence of metering of I-494 EB connector, the upstream ramps are required to store the excess demand. These ramps, individually, have substantially smaller queue storage capacities than the connector, so that many upstream ramps must be metered. The volumes exiting to I-494 are also large. Therefore, much of the traffic entering at the upstream ramps is not even destined for the bottleneck downstream of the I-494/I-35W interchange. As a result, it is necessary to store at these on ramps not only the excess demand for the bottleneck, but also a proportionate amount corresponding to vehicles exiting upstream of the bottleneck. In this instance, this increased storage requirement exceeds the storage capacity at the ramps for all but the most modest traffic demands. In summary, where ramp metering alone is not sufficient to handle the demand and where there is a high volume connector upstream of but near the bottleneck, ramp and connector metering is effective.

With a further review of the results presented in Tables 12 through 16, it is readily seen that mainline metering alone and ramp and mainline metering is generally less effective than ramp and connector metering. It should be noted, however, that only a single candidate location or mainline metering (at or near the upstream end of the segment considered) was examined in each case. It is quite possible that locating mainline metering nearer to the bottleneck would be more effective.

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6.0 SCENARIOS FOR SIMULATION

The evaluation procedures used in this study have limitations which precluded a complete assessment of the relative benefits of connector and mainline metering. Specifically, the models used here are not capable of representing the impact of extensive congestion on freeways, i.e., queueing which extends over several freeway sections, thereby obstructing egress from the freeway. Dynamic freeway simulation models are available which can be applied to complement the analyses undertaken here and which do provide means for measuring the impact of such extensive freeway congestion.

In the following section, these dynamic freeway simulations are identified, and the appropriate manner of application is discussed. The next section presents detailed simulation scenario data which can be used in these dynamic freeway simulations for the five sites which were the subject of evaluation as described in Section 5. These data also serve to document in detail the traffic situations which were examined there. The final subsection outlines a design of simulation experiments.

6.1 Objectives and Applications of Simulations

Three dynamic freeway simulations are available which would provide the capability to measure the impacts of extensive freeway congestion. Further, these simulations involve more refined representations of traffic flow behavior so that one would expect that their application would provide more accurate comparisons of alternative metering treatments.

Of these simulations, the FREQ series (of which FREQ6PE is the most widely used [JOVA78]) involves the simplest modeling approach. In fact, in the absence of freeway congestion, the models used in this study nearly coincide with the model underlying FREQ. (FREQ has a more detailed representation of merging impacts.) One immediate consequence is that the scenario data developed for use in this study can be immediately applied in FREQ.

The FREFLO simulation [PAYN78] is the macroscopic freeway simulation component of TRAFLO. An important modeling distinction between FREFLO and both FREQ and the models used in this study is that FREFLO handles exit volumes as specified fractions of upstream freeway volumes, while FREQ and the models used in this study represent all volumes in terms of components by destination. This has major importance where diversion is being considered and a secondary impact in controlling vehicles' trip patterns over variations in metering treatments.

The third dynamic freeway simulation, INTRAS, is a microscopic simulation [MICK77], i.e., individual vehicle movements are represented. This simulation provides a substantially more detailed representation of traffic flow at the cost of substantially more computational expense. INTRAS also handles exit volumes as fractions of upstream freeway volumes. Further, the freeway capacity is not an explicit model parameter.

Diversion is explicitly treated in FREQ. Moreover, the diversion model used in this study coincides with the "short trip" diversion option of FREQ. INTRAS and FREFLO have no mechanisms for representing diversion.

The computer programs embodying the FREQ simulation also include metering design via linear programming. Limited comparisons with designs obtained by the methods developed for this study show close agreement. The principal differences lie in the treatment of queue storage constraints: FREQ6PE, for example, cannot explicitly handle queue storage constraints.

In the following, simulation scenario data are provided for the five sites used in the evaluation presented in Section 5. These data served as inputs to the metering design and evaluation computer program used to obtain those evaluation results. They serve to define most, but not all, of the inputs necessary to execute FREQ, FREFLO (i.e., TRAFLO) or INTRAS. In making use of these data, the differences in modeling approaches embodied in these simulations, as described above, must be kept in mind.

The format of the data for each site is as follows:

(1) Entrance and exit locations, metering rate limits, entrance volume limits, queue storage limits, freeway capacity constraints and section lengths.

(2) Traffic demand volume data expressed as entrance/exit volumes by time-slice.

(3) Entrance/exit volume data; exit volumes are also expressed as fractions of upstream freeway volume.

(4) One or more metering plans specified as fixed rates in time slices and estimated diversion associated with the metering plan.

For Use in FREQ

(1) Geometric and constraint data can be used directly.

(2) The program SYNOD [ELDO73] can be applied to the entrance/exit volume data to produce OD demand volume data.

(3) Two options with respect to metering plans exit:

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(a) The metering plans presented here can be entered into FREQ, or

(b) The linear programming technique of FREQ6PE (for example) can be applied to determine metering rates; FREQ6PE can treat connectors and the mainline as ramps. However, FREQ6PE cannot explicitly account for queue storage constraints.

(4) With respect to diversion:

(a) The diverted traffic values provided here can be accepted, i.e., the remaining traffic treated as demand which does not divert. A separate accounting for the alternate route travel time need then be made, or

(b) One of the diversion model options of FREQ can be employed. The "short-tip" diversion model of FREQ coincides with the diversion model used to obtain the diversion data presented here.

For Use in INTRAS or FREFLO (TRAFLO)

(1) Geometric data can be used directly; other constraint data are not used in INTRAS or FREFLO.

(2) INTRAS and FREFLO represent exit volumes as specified fractions of through volumes. The indicated exit fractions may be used for this purpose, but it must be recognized that this technique is not the same as (or as accurate as) one based upon origin-destination data.

(3) The indicated metering rates define entrance volume data. As INTRAS and FREFLO do not model diversion, it would be necessary to accept the values of diverted traffic given here.

(4) The differences between entrance demand and undiverted volumes will then queue at ramps. INTRAS measures the delay due to this queueing and measures "frontage road" (i.e., alternate route) travel times.

The efficiency in assessment of metering alternatives under a variety of traffic situations is greatly aided by providing automation in the interface between metering plan specification and dynamic simulation. This has been provided for in the FREQ design/simulation packages. At present, use of FREFLO and INTRAS requires hand coding of metering specifications and associated diversion volumes and exit volume fractions.

6.2 Simulation Scenario Data

This section presents detailed simulation scenario data for each of five sites. These data are organized as indicated in Table 17 below.

Table 17. Organization of Simulation Scenario Data

Site	Geometric and Constraint Data	Traffic Demand Data	Entrance/Exit Volume Data	Metering Plans With Associated Queueing and Diversion
I-94, Westbound in San Diego	Table 18	Table 19	Table 20	Table 21
I-10, Eastbound in Los Angeles	Table 22	Table 23	Table 24	Table 25
I35-W, Southbound in Minneapolis	Table 26	Table 27	Table 28	Table 29
Rte 59, Inbound in Houston	Table 30	Table 31	Table 32	Table 33
I395 (Shirley Highway) Inbound in Virginia	Table 34	Table 35	Table 36	Table 37

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Table 18. Geometric and Constraint Data for I-15 Westbound in San Diego

PROFLEH STRUCTURE INPUT DATA

FREEWAY SPEED (MI/HR): 54.
ALTERNATE ROUTE SPEED (MI/HR): 25.
NUMBER OF SECTIONS: 40
NUMBER OF TIME SLICES: 9
DURATION OF EACH TIME SLICE (MIN): 15.
OD DEMAND VOLUME FILE: I94EXT.ODE
TOTAL OD VOLUME MULTIPLIER: 1.0400
RAMP CONSTRAINT OPTION (0 NO CONSTRAINT, 1 WITH CONSTRAINT): 1

	LOCATION	TYPE	MIN RAMP RATE	MAX RAMP RATE	VOL MAX RATE	QUE MAX (VEH)	FREEWAY CAPACITY	SECTION LENGTH	NUMBER OF LANES	AUXILIARY LANES
1	UPSTREAM	U ON	1000.	4000.	4000.	130.	4000.	0.00	1	
2	SPRING	OFF	0.	0.	0.	0.	4000.	1.40	2	D
3	SPRING	M ON	430.	1800.	3000.	36.	4000.	0.17	2	A
4	I-94	M ON	480.	3000.	4000.	73.	4000.	0.33	2	A
5	GROVE	OFF	0.	0.	0.	0.	6000.	0.10	3	F
6	LEMON GR	OFF	0.	0.	0.	0.	6000.	0.61	3	D
7	LEMON GR	M ON	240.	1200.	1500.	9.	6000.	0.17	3	A
8	HAITE	M ON	240.	900.	1500.	16.	8000.	0.30	4	A
9	MASSACH	OFF	0.	0.	0.	0.	8000.	0.20	4	D
10	MASSACH	M ON	240.	900.	1500.	20.	8000.	0.20	4	D
11	COLLEGE	OFF	0.	0.	0.	0.	8000.	0.33	4	D
12	BROADWAY	M ON	240.	900.	1500.	19.	8000.	0.07	4	F
13	COLLEGE	M ON	240.	900.	1500.	20.	8000.	0.07	4	F
14	COLL GRO	OFF	0.	0.	0.	0.	8000.	0.30	4	D
15	COLL GRO	M ON	480.	1800.	3000.	24.	8000.	0.09	4	F
16	FEDERAL	M ON	240.	900.	1500.	32.	8000.	1.31	4	A
17	KELTON	OFF	0.	0.	0.	0.	8000.	0.23	4	D
18	KELTON	M ON	480.	1800.	3000.	48.	8000.	0.17	4	A
19	EUCLID	OFF	0.	0.	0.	0.	8000.	0.30	4	D
20	EUCLD NB	M ON	240.	900.	1500.	16.	8000.	0.13	4	A
21	EUCLD SB	M ON	240.	900.	1500.	14.	8000.	0.08	4	F
22	47 TH ST	M ON	480.	1800.	3000.	8.	10000.	0.30	4	F
23	I-805	OFF	0.	0.	0.	0.	10000.	0.45	4	F
24	I-805	M ON	480.	2000.	4000.	170.	8000.	0.57	4	A
25	HOME	M ON	480.	1800.	3000.	32.	8000.	0.30	4	A
26	I-15 NB	OFF	0.	0.	0.	0.	8000.	0.09	4	F
27	I-15 NB	M ON	240.	900.	1500.	12.	8000.	0.17	4	A
28	I-15 SB	OFF	0.	0.	0.	0.	8000.	0.07	4	F
29	I-15 SB	M ON	480.	1800.	3000.	36.	8000.	0.07	4	F
30	32ND ST	OFF	0.	0.	0.	0.	10000.	0.36	4	F
31	32ND ST	M ON	240.	900.	1500.	14.	8000.	0.07	4	F
32	28TH ST	OFF	0.	0.	0.	0.	8000.	0.33	4	D
33	28TH ST	M ON	240.	900.	1500.	15.	8000.	0.13	4	A
34	25TH ST	OFF	0.	0.	0.	0.	8000.	0.33	4	D
35	I-5 NB	OFF	0.	0.	0.	0.	8000.	0.40	4	D
36	DWNSTREAM	THRU	0.	0.	0.	0.	6000.	0.20	3	
37	DES1	OFF	0.	0.	0.	0.	6000.	1.00	3	
38	DES2	OFF	0.	0.	0.	0.	6000.	1.00	3	
39	DES3	OFF	0.	0.	0.	0.	6000.	1.00	3	
40	DES4	OFF	0.	0.	0.	0.	6000.	1.00	3	

*A: acceleration lane (nominally 500 feet); D: deceleration lane (nominally 500 feet);
F: full (extends length of this section)

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Table 19. Traffic Demand Data for Rte 94 Westbound in San Diego

		DEMAND IN TIME SLICE (VEH/HR)								
ORIGIN LOCATION		1	2	3	4	5	6	7	8	9
1	UPSTREAM	2912	3037	3330	3742	3618	3492	2994	2498	2328
3	SPRING	82	164	164	124	209	163	80	83	80
4	I-94	1459	1750	2123	2246	2287	2037	1663	1580	1249
7	LEMON GR	831	748	788	957	998	791	707	581	539
8	WAITE	454	501	541	457	544	457	456	376	333
10	MASSACH	421	415	497	499	543	417	290	334	251
12	BROADWAY	207	208	291	165	251	208	251	248	208
13	COLLEGE	413	415	375	456	456	291	375	373	293
15	COLL GRO	124	125	86	208	123	82	81	86	124
16	FEDERAL	788	747	666	791	788	706	582	541	499
18	KELTON	210	210	292	207	291	166	250	127	128
20	EUCLD NB	457	414	333	291	334	414	207	249	292
21	EUCLD SB	541	540	496	626	709	791	498	541	497
22	47TH ST	124	168	168	211	207	167	165	167	164
24	I-805	1621	1457	1664	1458	1457	1372	1250	1121	917
25	HOME	750	706	790	831	955	1038	583	582	498
27	I-15 NB	125	127	82	126	167	126	168	165	82
29	I-15 SB	832	916	874	874	873	917	831	833	748
31	32ND ST	83	41	41	81	82	126	82	81	81
33	28TH ST	84	44	44	83	43	83	40	84	83
DESTINATION LOCATION		1	2	3	4	5	6	7	8	9
2	SPRING	250	208	250	250	250	333	374	416	333
5	GROVE	125	166	166	291	333	374	333	291	250
6	LEMON GR	42	42	83	125	125	208	291	126	208
9	MASSACH	126	125	83	167	250	291	290	291	291
11	COLLEGE	209	166	249	374	374	499	332	374	291
14	COLL GRO	125	125	83	125	209	165	124	84	83
17	KELTON	208	208	290	374	582	375	292	166	164
19	EUCLID	124	208	167	208	208	207	251	251	166
23	I-805	2078	2579	2747	3204	2994	2330	2372	1914	1832
26	I-15 NB	41	40	84	42	41	41	42	83	42
28	I-15 SB	1205	1039	916	790	790	583	374	374	376
30	32ND ST	333	373	500	543	583	458	373	416	375
32	28TH ST	626	415	415	499	250	290	290	207	209
34	25TH ST	499	707	582	664	582	584	460	418	415
35	I-5 NB	3451	3124	3577	3411	3536	2643	2827	2165	1995

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Table 20. Entrance/Exit Volume Data for Rte 94 Westbound in San Diego

			TIME SLICE 1		TIME SLICE 2		TIME SLICE 3		TIME SLICE 4		TIME SLICE 5		TIME SLICE 6		TIME SLICE 7		TIME SLICE 8		TIME SLICE 9	
	LOCATION	TYPE	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF
1	UPSTREAM	U ON	2912		3037		3330		3742		3618		3092		2994		2498		2328	
2	SPRING	OFF	-250	.0857	-208	.0685	-250	.0750	-250	.0667	-250	.0690	-333	.0953	-374	.1250	-416	.1665	-333	.1430
3	SPRING	M ON	82		164		164		124		209		163		80		83		80	
4	I-94	M ON	1459		1750		2123		2246		2050		2246		1663		1580		1249	
5	GROVE	OFF	-125	.0297	-166	.0351	-166	.0310	-291	.0497	-320	.0567	-374	.0672	-333	.0763	-291	.0778	-250	.0751
6	LEMON GR	OFF	-42	.0102	-42	.0091	-83	.0160	-125	.0224	-120	.0226	-208	.0400	-291	.0723	-126	.0364	-208	.0677
7	LEMON GR	M ON	831		748		788		957		962		827		707		581		539	
8	WHITE	M ON	454		501		541		421		505		521.		456		376		333	
9	MASSACH	OFF	-126	.0236	-125	.0216	-83	.0129	-167	.0244	-238	.0358	-380	.0474	-290	.0692	-291	.0679	-291	.0779
10	MASSACH	M ON	421		415		497		413		537		027		290		334		251	
11	COLLEGE	OFF	-209	.0372	-166	.0274	-249	.0362	-368	.0521	-355	.0510	-511	.0783	-332	.0677	-374	.0865	-291	.0788
12	BROADWAY	M ON	207		208		291		165		240		218		251		248		208	
13	COLLEGE	M ON	413		415		375		368		448		371		375		373		293	
14	COLL GRO	OFF	-125	.0207	-125	.0191	-83	.0114	-121	.0168	-197	.0270	-172	.0259	-124	.0238	-84	.0184	-83	.0213
15	COLL GRO	M ON	124		125		86		208		123		82		81		86		124	
16	FEDERAL	M ON	788		747		642		677		777		834		582		541		499	
17	KELTON	OFF	-208	.0305	-208	.0296	-289	.0365	-360	.0450	-548	.0685	-401	.0546	-292	.0510	-166	.0325	-164	.0369
18	KELTON	M ON	210		210		292		207		291		166		250		127		128	
19	EUCLID	OFF	-124	.0182	-208	.0296	-167	.0211	-200	.0255	-197	.0255	-218	.0306	-251	.0440	-251	.0494	-166	.0377
20	EUCLD NB	M ON	457		414		240		345		334		414		207		249		292	
21	EUCLD SB	M ON	541		540		496		626		709		791		498		541		497	
22	47TH ST	M ON	124		168		168		211		297		167		165		167		164	
23	I-805	OFF	-2078	.2659	-2579	.3148	-2711	.3128	-3101	.3512	-2923	.3323	-2511	.3035	-2372	.3758	-1914	.3308	-1832	.3525
24	I-805	M ON	1612		1467		1426		1396		1086		1133		1518		1121		917	
25	HOME	M ON	565		831		618		789		930		1016		711		582		498	
26	I-15 NB	OFF	-39	.0050	-40	.0050	-80	.0099	-39	.0049	-37	.0046	-39	.0050	-42	.0067	-83	.0149	-42	.0087
27	I-15 NB	M ON	125		127		82		126		167		126		168		165		82	
28	I-15 SB	OFF	-1177	.1471	-1040	.1300	-864	.1080	-737	.0922	-716	.0896	-577	.0722	-374	.0595	-374	.0662	-376	.0781
29	I-15 SB	M ON	832		916		874		874		873		903		846		833		748	
30	32ND ST	OFF	-326	.0426	-374	.0474	-475	.0592	-510	.0627	-533	.0654	-451	.0542	-374	.0553	-416	.0680	-375	.0723
31	32ND ST	M ON	83		41		41		81		82		126		82		81		81	
32	28TH ST	OFF	-613	.0827	-415	.0551	-394	.0520	-472	.0613	-233	.0303	-283	.0353	-291	.0449	-207	.0358	-209	.0427
33	28TH ST	M ON	84		44		44		83		43		83		48		84		83	
34	25TH ST	OFF	-489	.0710	-708	.0987	-553	.0765	-640	.0875	-547	.0728	-578	.0741	-470	.0755	-418	.0739	-415	.0869
35	I-5 NB	OFF	-3380	.5205	-3194	.4941	-3395	.5009	-3363	.5036	-3354	.4814	-2665	.3698	-2877	.4999	-2165	.4133	-1995	.4578
36	DOWNSTREAM	THRU	0		0		0		0		0		0		0		0		0	

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Table 21. Ramp and Connector Metering Plan, with Associated Queueing and Diversion for Rte 94 Westbound in San Diego

SUMMARY OF METERING PLAN
WITH DIVERSION

TIME SLICE		ENTRANCE LOCATION 1 UPSTREAM	3 SPRING	4 I-94	7 LEMON GR	8 WAITE	10 MASSACH	12 BROADWAY	13 COLLEGE	15 COLL GRO	16 FEDERAL
1	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	642.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4	METERING RATE	0.	0.	0.	0.	421.	413.	0.	368.	0.	677.
	QUEUED VEH	0.	0.	0.	0.	8.	20.	0.	20.	0.	32.
	DIVERTED VEH	0.	0.	0.	0.	1.	1.	0.	2.	0.	2.
5	METERING RATE	0.	0.	2060.	562.	505.	537.	240.	448.	0.	777.
	QUEUED VEH	0.	0.	52.	9.	16.	20.	3.	20.	0.	32.
	DIVERTED VEH	0.	0.	4.	0.	2.	1.	0.	2.	0.	3.
6	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
8	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
9	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Table 21. Ramp and Connector Metering Plan, with Associated Queueing and Diversion for Rte 94 Westbound in San Diego (continued)

SUMMARY OF METERING PLAN
WITH DIVERSION

TIME SLICE		ENTRANCE LOCATION 18 KELTON	20 EUCLD NB	21 EUCLD SB	22 47 TH ST	24 I-805	25 HOME	27 I-15 NB	29 I-15 SB	31 32ND ST	33, 28TH ST
1	METERING RATE	0.	0.	0.	0.	1612.	565.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	2.	32.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	14.	0.	0.	0.	0.
2	METERING RATE	0.	0.	0.	0.	0.	831.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	1.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3	METERING RATE	0.	240.	0.	0.	1426.	618.	0.	0.	0.	0.
	QUEUED VEH	0.	13.	0.	0.	47.	32.	0.	0.	0.	0.
	DIVERTED VEH	0.	10.	0.	0.	13.	12.	0.	0.	0.	0.
4	METERING RATE	0.	0.	0.	0.	1396.	789.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	51.	32.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	12.	10.	0.	0.	0.	0.
5	METERING RATE	0.	0.	0.	0.	1066.	930.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	60.	32.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	89.	6.	0.	0.	0.	0.
6	METERING RATE	0.	0.	0.	0.	1133.	1016.	0.	903.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	67.	32.	0.	4.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	52.	5.	0.	0.	0.	0.
7	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
8	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
9	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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Table 22. Geometric and Constraint Data for I-10 Eastbound in Los Angeles

PROBLEM STRUCTURE INPUT DATA

FREEWAY SPEED (MI/HR): 54.
ALTERNATE ROUTE SPEED (MI/HR): 25.
NUMBER OF SECTIONS: 28
NUMBER OF TIME SLICES: 10
DURATION OF EACH TIME SLICE (MIN): 15.
OD DEMAND VOLUME FILE: I10EXT.ODE
TOTAL OD VOLUME MULTIPLIER: 1.0000
RAMP CONSTRAINT OPTION (0 NO CONSTRAINT, 1 WITH CONSTRAINT): 1

	LOCATION	TYPE	MIN RAMP RATE	MAX RAMP RATE	VOL MAX RATE	QUE MAX (VEH)	FREEWAY CAPACITY	SECTION LENGTH	NUMBER OF LANES	AUXILIARY* LANES
1	UPSTREAM	U ON	1000.	6000.	6000.	200.	6000.	0.00		
2	I405-SB	M ON	480.	4000.	4000.	225.	10000.	0.00	5	
3	I405-NB	M ON	480.	2000.	3000.	80.	10000.	0.00	5	
4	OVERLAND	OFF	0.	0.	0.	0.	10000.	0.59	5	
5	OVERLAND	M ON	480.	1800.	3000.	69.	8000.	0.16	4	A
6	MANNING	M ON	240.	900.	1500.	40.	8000.	0.68	4	A
7	ROBERTSN	OFF	0.	0.	0.	0.	8000.	0.46	4	D
8	ROBERTSN	M ON	240.	900.	1500.	28.	8000.	0.32	4	A
9	LACIENGA	OFF	0.	0.	0.	0.	8000.	0.51	4	D
10	FAIRFAX	OFF	0.	0.	0.	0.	8000.	0.51	4	D
11	LACIENGA	M ON	480.	1800.	3000.	54.	8000.	0.21	4	A
12	WASHINGT	M ON	480.	1800.	3000.	65.	8000.	0.30	4	A
13	LA BREA	OFF	0.	0.	0.	0.	10000.	0.68	5	D
14	LABREA	M ON	480.	1800.	3000.	64.	10000.	0.51	5	A
15	CRENSHAW	OFF	0.	0.	0.	0.	10000.	0.51	5	D
16	CRENSHAW	M ON	480.	1800.	3000.	50.	10000.	0.34	5	A
17	ARLINGTO	OFF	0.	0.	0.	0.	12000.	0.63	6	D
18	WEST/NOR	OFF	0.	0.	0.	0.	12000.	0.27	6	D
19	ARLINGTO	M ON	480.	1800.	3000.	34.	12000.	0.27	6	A
20	VERM/HOO	OFF	0.	0.	0.	0.	12000.	0.48	6	D
21	WEST/NOR	M ON	480.	1800.	3000.	44.	12000.	0.35	6	A
22	HARBOR	OFF	0.	0.	0.	0.	12000.	0.40	6	D
23	VERMONT	M ON	480.	1800.	3000.	36.	6000.	0.42	3	A
24	DWSTREAM	THRU	0.	0.	0.	0.	6000.	0.27	3	
25	DES1	OFF	360.	900.	1500.	0.	6000.	1.00	3	
26	DES2	OFF	0.	0.	0.	0.	6000.	1.00	3	
27	DES3	OFF	360.	900.	1500.	0.	6000.	1.00	3	
28	DES4	OFF	0.	0.	0.	0.	6000.	1.00	3	

*A: acceleration lane (nominally 500 feet); D: deceleration lane (nominally 500 feet);
F: full (extends length of this section)

Table 23. Traffic Demand Data for I-10 Eastbound in Los Angeles

	DEMAND IN TIME SLICE (VEH/HR)									
ORIGIN LOCATION	1	2	3	4	5	6	7	8	9	10
1 UPSTREAM	3444	3656	3504	3336	3396	3652	3612	3504	3440	3440
2 I-405 SB	1816	1940	1852	1764	1796	1936	1908	1856	1816	1816
3 I-405 NB	1236	1316	1256	1192	1220	1320	1284	1256	1236	1232
5 OVERLAND	968	1048	840	796	800	788	812	764	764	756
6 MANNING	552	696	632	680	520	552	560	592	548	528
8 ROBERTSN	440	396	448	388	344	352	480	500	504	484
11 LACIENGA	700	864	744	760	712	784	816	784	824	720
12 WASHINGT	1112	1304	1304	1360	992	1032	1000	1056	996	896
14 LA BREA	1308	1612	1588	1560	1252	1240	1252	1220	1180	1148
16 CRENSHAW	1052	1272	1320	1404	1460	1380	1232	1096	1024	904
19 ARLINGTO	620	904	1004	1200	1124	1000	1004	896	600	444
21 WEST/NOR	904	1100	1240	1500	1424	1108	1040	864	676	728
23 VERMONT	480	516	544	596	560	480	384	384	320	304
DESTINATION LOCATION	1	2	3	4	5	6	7	8	9	10
4 OVERLAND	420	520	900	1200	1200	1360	1404	1360	1300	1160
7 ROBERTSN	396	300	364	436	596	496	536	484	520	580
9 LACIENGA	340	324	400	524	596	600	720	680	764	556
10 FAIRFAX	240	260	380	380	564	476	540	464	480	484
13 LA BREA	244	244	280	280	364	356	420	396	440	500
15 CRENSHAW	244	204	208	156	236	240	240	236	320	384
17 ARLINGTO	96	104	108	156	200	196	204	200	200	200
18 WEST/NOR	492	340	364	356	388	520	444	540	540	540
20 VERM/HOO	916	1004	1140	1284	1440	1516	1636	1800	1788	1544
22 HARBOR	5624	6660	6060	5880	5008	4936	4616	4308	3792	3720

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Table 24. Entrance/Exit Volume Data for I-10 Eastbound in Los Angeles

			TIME SLICE 1		TIME SLICE 2		TIME SLICE 3		TIME SLICE 4		TIME SLICE 5		TIME SLICE 6		TIME SLICE 7		TIME SLICE 8		TIME SLICE 9		TIME SLICE 10	
	LOCATION	TYPE	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF
1	UPSTREAM	M ON	3484		3656		3804		3336		3396		3652		3612		3504		3440		3480	
2	I-405 SB	M ON	1836		1940		1862		1764		1796		1936		1908		1856		1816		1816	
3	I-405 NB	M ON	1236		1316		1256		1192		1220		1320		1284		1256		1236		1232	
4	OVERLAND	OFF	-420	.0647	-520	.0752	-900	.1361	-1280	.1907	-1280	.1871	-1360	.1960	-1404	.2063	-1360	.2056	-1300	.2002	-1160	.1788
5	OVERLAND	M ON	968		880		993		796		880		788		812		764		764		756	
6	HANNING	M ON	552		513		661		795		520		552		560		592		548		520	
7	ROBERTSN	OFF	-396	.0521	-288	.0360	-350	.0487	-436	.0652	-596	.0912	-496	.0720	-536	.0791	-484	.0732	-520	.0800	-580	.0877
8	ROBERTSN	M ON	440		256		435		500		344		352		480		500		504		484	
9	LACIENGA	OFF	-340	.0445	-305	.0393	-395	.0531	-524	.0777	-596	.0949	-680	.0890	-720	.1072	-680	.1026	-764	.1178	-556	.0853
10	FAIRFAX	OFF	-240	.0329	-246	.0329	-374	.0531	-388	.0611	-564	.0992	-476	.0775	-540	.0901	-484	.0788	-480	.0839	-484	.0812
11	LACIENGA	M ON	700		630		726		976		712		784		816		784		824		720	
12	WASHINGT	M ON	1112		1030		1292		1620		992		1032		1000		1056		996		896	
13	LA BREA	OFF	-244	.0275	-221	.0249	-265	.0306	-283	.0335	-364	.0533	-356	.0476	-420	.0570	-396	.0541	-440	.0623	-500	.0705
14	LA BREA	M ON	1308		1342		1573		1642		1423		1240		1252		1220		1180		1148	
15	CRENSHAW	OFF	-244	.0246	-182	.0182	-197	.0197	-158	.0161	-236	.0299	-240	.0287	-240	.0296	-236	.0290	-320	.0410	-304	.0496
16	CRENSHAW	M ON	1052		1272		1320		1166		1660		1380		1232		1096		1024		901	
17	ARLINGTO	OFF	-96	.0089	-94	.0084	-102	.0092	-154	.0143	-202	.0217	-196	.0206	-204	.0224	-200	.0222	-200	.0235	-200	.0242
18	WEST/VER	OFF	-492	.0462	-368	.0298	-352	.0319	-357	.0336	-393	.0432	-520	.0888	-404	.0499	-548	.0613	-540	.0650	-540	.0670
19	ARLINGTO	M ON	620		904		874		1164		1260		1080		1004		896		880		644	
20	VERM/VER	OFF	-916	.0850	-935	.0789	-1127	.0876	-1312	.1045	-1459	.1483	-1516	.1548	-1636	.1731	-1880	.1964	-1780	.2137	-1544	.1939
21	WEST/VER	M ON	904		820		1041		1342		1600		1100		1040		864		676		720	
22	HARBOR	OFF	-5624	.5225	-5678	.5199	-5938	.5183	-5871	.5196	-5261	.5202	-4936	.5260	-4616	.5212	-4388	.5236	-3792	.5226	-3720	.5204
23	VERMONT	M ON	480		480		480		480		660		480		384		384		320		304	
24	DWNSTREAM	THRU	0		0		0		0		0		0		0		0		0		0	

Table 25. Ramp and Connector Metering Plan, with Associated Queueing and Diversion for I-10 Eastbound in Los Angeles

SUMMARY OF METERING PLAN WITH DIVERSION

TIME SLICE		ENTRANCE LOCATION 1 UPSTREAM	2 I405-SB	3 I405-NB	5 OVERLAND	6 MANNING	8 ROBERTSN	11 LACIENGA	12 WASHINGT	14 LABREA	16 CRENSHAW	19 ARLINGTO	21 WEST/AVR	23 VERMONT
1	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	METERING RATE	0.	0.	0.	889.	513.	295.	630.	1039.	1342.	0.	0.	820.	480.
	QUEUED VEH	0.	0.	0.	38.	40.	28.	54.	88.	64.	0.	0.	34.	9.
	DIVERTED VEH	0.	0.	0.	2.	6.	5.	5.	4.	4.	0.	0.	36.	0.
3	METERING RATE	0.	0.	0.	0.	681.	435.	726.	1232.	1573.	0.	874.	1041.	480.
	QUEUED VEH	0.	0.	0.	0.	29.	28.	64.	85.	64.	0.	25.	44.	19.
	DIVERTED VEH	0.	0.	0.	0.	4.	3.	4.	3.	4.	0.	3.	39.	6.
4	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	1642.	1106.	1164.	1342.	480.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	43.	58.	34.	44.	25.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	1.	9.	4.	39.	23.
5	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
6	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
8	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
9	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
10	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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Table 26. Geometric and Constraint Data for I-35W Southbound in Minneapolis

PROBLEM STRUCTURE INPUT DATA

FREEWAY SPEED (MI/HR): 54.
ALTERNATE ROUTE SPEED (MI/HR): 25.
NUMBER OF SECTIONS: 36
NUMBER OF TIME SLICES: 15
DURATION OF EACH TIME SLICE (MIN): 15.
OD DEMAND VOLUME FILE: I35EXT.ODE
TOTAL OD VOLUME MULTIPLIER: 0.7500
RAMP CONSTRAINT OPTION (0 NO CONSTRAINT, 1 WITH CONSTRAINT): 1

	LOCATION	TYPE	MIN RAMP RATE	MAX RAMP RATE	VOL MAX RATE	QUE MAX (VEH)	FREEWAY CAPACITY	SECTION LENGTH	NUMBER OF LANES	AUXILIARY* LANES
1	UPSTREAM	M ON	480.	1800.	3000.	72.	4000.	0.00		
2	12TH	M ON	240.	900.	1500.	68.	4000.	1.00	2	A
3	I-94	M ON	240.	900.	1500.	64.	4000.	0.21	2	A
4	MAINLINE	U ON	480.	4000.	4200.	300.	6000.	0.53	3	
5	31ST	M ON	240.	900.	1500.	16.	8000.	0.34	4	A
6	35TH	OFF	0.	0.	0.	0.	8000.	0.11	4	A
7	36TH	M ON	240.	900.	1500.	24.	8000.	0.56	4	A
8	46TH	OFF	0.	0.	0.	0.	8000.	0.76	4	A
9	46TH	M ON	240.	900.	1500.	20.	6000.	0.45	3	A
10	DIAMOND	OFF	0.	0.	0.	0.	6000.	0.61	3	A
11	DIAMOND	M ON	240.	900.	1500.	24.	6000.	0.51	3	A
12	60TH	OFF	0.	0.	0.	0.	6000.	0.28	3	A
13	62ND	OFF	0.	0.	0.	0.	6000.	0.28	3	D
14	HWY 100	M ON	480.	1800.	3000.	90.	4000.	0.26	2	D
15	66TH	OFF	0.	0.	0.	0.	4000.	0.19	2	A
16	66TH	M ON	240.	900.	1500.	24.	4000.	0.32	2	A
17	76TH	OFF	0.	0.	0.	0.	4000.	0.91	2	A
18	I-494WB	OFF	0.	0.	0.	0.	4000.	0.25	2	D
19	I-494WB	M ON	240.	900.	1500.	28.	4000.	0.11	2	D
20	I-494EB	OFF	0.	0.	0.	0.	4000.	0.08	2	F
21	I-494EB	M ON	240.	900.	1500.	96.	4000.	0.11	2	F
22	82ND	OFF	0.	0.	0.	0.	4000.	0.18	2	F
23	82ND	M ON	240.	900.	1500.	8.	4000.	0.22	2	D
24	90TH	OFF	0.	0.	0.	0.	4000.	0.79	2	A
25	90TH	M ON	240.	900.	1500.	22.	4000.	0.22	2	D
26	94TH	OFF	0.	0.	0.	0.	4000.	0.30	2	A
27	94TH	M ON	240.	900.	1500.	44.	4000.	0.26	2	D
28	98TH	OFF	0.	0.	0.	0.	4000.	0.24	2	A
29	98TH	M ON	240.	900.	1500.	40.	4000.	0.39	2	D
30	106TH	OFF	0.	0.	0.	0.	4000.	0.72	2	A
31	106TH	M ON	240.	900.	1500.	36.	4000.	0.24	2	D
32	DOWNSTRE	THRU	0.	0.	0.	0.	4000.	0.78	2	A
33	DES1	OFF	0.	0.	0.	0.	4000.	1.00	2	
34	DES2	OFF	0.	0.	0.	0.	4000.	1.00	2	
35	DES3	OFF	0.	0.	0.	0.	4000.	1.00	2	
36	DES4	OFF	0.	0.	0.	0.	4000.	1.00	2	

*A: acceleration lane (nominally 500 feet); D: deceleration lane (nominally 500 feet);
F: full (extends length of this section)

Table 27. Traffic Demand Data for I-35W Southbound in Minneapolis

	DEMAND IN TIME SLICE (VEH/HR)									
ORIGIN LOCATION	1	2	3	4	5	6	7	8	9	10
1 UPSTREAM	1251	1129	1239	1476	1407	1229	1348	1691	1626	1413
2 12TH	287	240	262	349	349	393	384	499	406	290
3 I-94	568	502	493	661	521	524	465	574	502	612
4 MAINLINE	2178	2652	2490	2406	2705	2852	3173	2462	2699	2343
5 31ST	374	315	306	287	228	243	218	231	231	234
7 36TH	209	212	159	234	156	175	150	165	168	165
9 46TH	144	119	147	172	137	159	134	134	147	144
11 DIAMOND	109	131	128	137	100	94	100	103	125	97
14 HWY 190	580	693	571	552	702	624	877	749	661	696
16 66TH	178	122	159	259	250	159	165	134	225	172
19 I-494 WB	421	415	499	480	477	431	427	471	449	371
21 I-494 EB	593	649	649	699	696	696	752	686	630	618
23 82ND	197	187	181	200	212	181	206	193	222	156
25 90TH	165	190	209	159	175	175	184	147	159	150
27 94TH	153	193	243	140	153	178	165	128	125	103
29 98TH	178	315	281	321	331	318	306	268	215	218
31 106TH	150	225	240	262	324	324	328	275	225	212
DESTINATION LOCATION	1	2	3	4	5	6	7	8	9	10
6 35TH	418	468	468	468	512	596	686	749	714	618
8 46TH	434	474	490	446	574	608	714	761	727	630
10 DIAMOND	243	172	256	237	290	240	331	346	365	356
12 60TH	119	137	184	190	206	231	187	178	175	159
13 62ND	914	855	1033	905	1126	936	942	945	961	870
15 66TH	153	125	222	159	175	200	284	209	250	209
17 76TH	184	153	187	212	197	250	284	243	197	243
18 I-494 WB	437	390	368	362	402	337	315	477	474	399
20 I-494 EB	168	197	175	159	203	175	178	150	137	165
22 82ND	243	265	293	306	287	250	387	353	262	212
24 90TH	256	234	250	234	197	172	150	137	159	144
26 94TH	296	197	215	203	156	144	156	144	128	150
28 98TH	321	365	346	365	343	290	306	312	324	346
30 106TH	66	50	62	106	81	69	78	97	69	78

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Table 28. Entrance/Exit Volume Data for I-35W Southbound in Minneapolis

			TIME SLICE 1		TIME SLICE 2		TIME SLICE 3		TIME SLICE 4		TIME SLICE 5		TIME SLICE 6		TIME SLICE 7		TIME SLICE 8		TIME SLICE 9		TIME SLICE 10	
	LOCATION	TYPE	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF
1	UPSTREAM	M ON	1251		1129		1239		1476		1407		1229		1348		1691		1626		1413	
2	12TH	M ON	287		240		262		349		349		393		384		499		486		290	
3	I-94	M ON	568		502		493		640		542		624		486		574		502		612	
4	MASELINE	U ON	2170		2652		2490		2486		2705		2852		3173		2462		2699		2343	
5	31ST	M ON	374		315		306		240		267		243		218		231		231		234	
6	35TH	OFF	-418	.0898	-468	.0957	-468	.0977	-462	.0904	-514	.0974	-596	.1137	-605	.1228	-749	.1372	-714	.1388	-618	.1263
7	36TH	M ON	209		212		159		234		156		175		150		165		168		165	
8	46TH	OFF	-434	.0975	-474	.1035	-490	.1093	-440	.0902	-576	.1172	-688	.1262	-714	.1414	-761	.1562	-727	.1478	-630	.1420
9	46TH	M ON	144		119		147		172		137		159		134		134		147		144	
10	DIAMOND	OFF	-243	.0585	-172	.0406	-256	.0618	-234	.0508	-293	.0655	-240	.0550	-331	.0748	-306	.0816	-305	.0842	-356	.0900
11	DIAMOND	M ON	109		131		128		137		100		94		100		103		125		97	
12	60TH	OFF	-119	.0295	-137	.0328	-184	.0459	-188	.0416	-208	.0486	-231	.0547	-187	.0442	-178	.0444	-175	.0427	-159	.0431
13	62ND	OFF	-914	.2340	-855	.2111	-1033	.2700	-894	.2066	-1137	.2791	-936	.2344	-942	.2325	-945	.2471	-961	.2450	-870	.2462
14	HWY 190	M ON	580		693		571		480		748		624		877		749		661		696	
15	66TH	OFF	-153	.0428	-125	.0321	-222	.0659	-155	.0395	-176	.0476	-208	.0542	-284	.0712	-289	.0576	-258	.0689	-209	.0622
16	66TH	M ON	178		122		159		240		269		159		165		134		225		172	
17	76TH	OFF	-184	.0512	-153	.0394	-187	.0567	-265	.0614	-200	.0526	-250	.0686	-284	.0734	-243	.0685	-197	.0546	-243	.0732
18	I-494 WB	OFF	-437	.1280	-390	.1045	-368	.1182	-351	.0924	-414	.1151	-337	.0994	-315	.0879	-477	.1442	-474	.1394	-399	.1297
19	I-494 WB	M ON	421		415		499		470		487		431		427		471		499		371	
20	I-494 EB	OFF	-168	.0496	-197	.0523	-175	.0538	-154	.0394	-207	.0565	-175	.0501	-178	.0481	-158	.0453	-137	.0407	-165	.0542
21	I-494 EB	M ON	593		448		807		240		537		532		412		846		724		644	
22	82ND	OFF	-243	.0637	-252	.0638	-293	.0757	-267	.0668	-276	.0689	-230	.0599	-346	.0879	-344	.0860	-260	.0657	-212	.0601
23	82ND	M ON	197		187		181		200		212		181		286		193		222		156	
24	90TH	OFF	-256	.0678	-223	.0567	-250	.0663	-206	.0529	-190	.0483	-158	.0419	-135	.0355	-134	.0349	-158	.0403	-144	.0416
25	90TH	M ON	165		190		209		159		175		175		184		147		159		150	
26	94TH	OFF	-296	.0804	-188	.0481	-215	.0578	-179	.0462	-151	.0386	-134	.0361	-141	.0367	-141	.0364	-130	.0331	-151	.0433
27	94TH	M ON	153		193		243		140		153		178		165		128		125		103	
28	98TH	OFF	-321	.0907	-349	.0893	-346	.0923	-324	.0843	-332	.0847	-271	.0702	-278	.0718	-305	.0793	-329	.0840	-348	.1015
29	98TH	M ON	178		263		332		321		247		240		240		310		240		245	
30	106TH	OFF	-66	.0193	-47	.0124	-52	.0167	-96	.0248	-77	.0201	-62	.0163	-68	.0177	-94	.0243	-70	.0183	-78	.0236
31	106TH	M ON	150		225		240		252		240		240		240		240		240		271	
32	DOWNSTRE	THRU	0		0		0		0		0		0		0		0		0		0	

Table 29. Ramp and Connector Metering Plan, with Associated Queueing and Diversion for I-35W Southbound in Minneapolis

SUMMARY OF METERING PLAN WITH DIVERSION

TIME SLICE		ENTRANCE LOCATION 1 UPSTREAM	2 12TH	3 I-94	4 MAINLINE	5 31ST	7 38TH	9 46TH	11 DIAMOND	14 HWY 150	16 66TH	19 I-494WB	21 I-494EB	23 62ND	25 58TH	27 54TH	29 50TH	31 19STH
1	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	440.	0.	0.	0.	263.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	38.	0.	0.	0.	13.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	13.	0.	0.	0.	0.	0.
3	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4	METERING RATE	0.	0.	840.	0.	240.	0.	0.	0.	480.	240.	470.	240.	0.	0.	0.	0.	252.
	QUEUED VEH	0.	0.	0.	0.	10.	0.	0.	0.	18.	0.	2.	44.	0.	0.	0.	0.	3.
	DIVERTED VEH	0.	0.	0.	0.	2.	0.	0.	0.	2.	0.	0.	71.	0.	0.	0.	0.	0.
5	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	537.	0.	0.	0.	247.	240.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	67.	0.	0.	0.	15.	18.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	16.	0.	0.	0.	6.	6.
6	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	832.	0.	0.	0.	240.	240.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	71.	0.	0.	0.	27.	21.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	37.	0.	0.	0.	8.	18.
7	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	412.	0.	0.	0.	240.	240.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	73.	0.	0.	0.	33.	26.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	83.	0.	0.	0.	28.	17.
8	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	848.	0.	0.	0.	310.	240.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	38.	0.	0.	0.	13.	22.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.	0.	0.	0.	0.	12.
9	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	724.	0.	0.	0.	240.	240.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.	0.	0.	0.	7.	15.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.
10	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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Table 30. Geometric and Constraint Data for Route 59, Inbound in Houston

PROBLEM STRUCTURE INPUT DATA

FREEWAY SPEED (MI/HR): 54.
ALTERNATE ROUTE SPEED (MI/HR): 25.
NUMBER OF SECTIONS: 29
NUMBER OF TIME SLICES: 10
DURATION OF EACH TIME SLICE (MIN): 15.
OD DEMAND VOLUME FILE: HSTEXT.ODE
TOTAL OD VOLUME MULTIPLIER: 1.0000
RAMP CONSTRAINT OPTION (0 NO CONSTRAINT, 1 WITH CONSTRAINT): 0

	LOCATION	TYPE	MIN RAMP RATE	MAX RAMP RATE	VOL MAX RATE	QUE MAX (VEH)	FREEWAY CAPACITY	SECTION LENGTH	NUMBER OF LANES	AUXILIARY* LANES
1	BISSONNE	M ON	2000.	6000.	6000.	600.	6000.	0.00		
2	BISSONNE	M ON	480.	1800.	3000.	36.	6000.	0.48	3	
3	GESSNER	OFF	0.	0.	0.	0.	6000.	0.62	3	
4	BEECHNUT	M ON	480.	1800.	3000.	40.	6000.	0.75	3	
5	FONDREN	OFF	0.	0.	0.	0.	6000.	0.33	3	
6	FONDREN	M ON	240.	900.	1500.	40.	6000.	0.38	3	
7	BELLAIRE	M ON	480.	1800.	3000.	88.	6000.	0.62	3	
8	HILLCROF	OFF	0.	0.	0.	0.	6000.	0.39	3	
9	HILLCROF	M ON	480.	1800.	3000.	60.	6000.	0.63	3	
10	WESTPARK	M ON	480.	1800.	3000.	56.	6000.	0.72	3	
11	CHIMNEY	OFF	0.	0.	0.	0.	8000.	0.39	4	
12	CHIMNEY	M ON	480.	1800.	3000.	104.	6000.	0.46	4	
13	I-610	OFF	0.	0.	0.	0.	8000.	0.43	4	
14	I-610	M ON	2000.	5000.	5000.	180.	6000.	0.52	3	
15	NEWCASTL	OFF	0.	0.	0.	0.	10000.	0.24	5	
16	NEWCASTL	M ON	480.	1800.	3000.	12.	10000.	0.24	5	
17	WESLAYAN	OFF	0.	0.	0.	0.	10000.	0.32	5	
18	EDLOE	OFF	0.	0.	0.	0.	10000.	0.37	5	
19	EDLOE	M ON	480.	1800.	3000.	28.	8000.	0.46	4	
20	BUFFALO	M ON	480.	1800.	3000.	28.	8000.	0.32	4	
21	KIRBY DR	OFF	0.	0.	0.	0.	10000.	0.32	5	
22	KIRBY DR	M ON	480.	1800.	3000.	40.	8000.	0.24	4	
23	GREENBRI	OFF	0.	0.	0.	0.	10000.	0.11	5	
24	SHEPERD	M ON	240.	900.	1500.	40.	8000.	0.41	4	
25	DWSTREAM	THRU	0.	0.	0.	0.	10000.	1.20	5	
26	DES1	OFF	0.	0.	0.	0.	10000.	1.00	5	
27	DES2	OFF	0.	0.	0.	0.	10000.	1.00	5	
28	DES3	OFF	0.	0.	0.	0.	10000.	1.00	5	
29	DES4	OFF	0.	0.	0.	0.	10000.	1.00	5	

*Ramps are all slip ramps without a significant auxiliary acceleration or deceleration lane.

Table 31. Traffic Demand Data for Route 59, Inbound in Houston

		DEMAND IN TIME SLICE (VEH/HR)									
ORIGIN LOCATION		1	2	3	4	5	6	7	8	9	10
1	BISSONNE	1800	2776	3944	4064	4600	3348	2980	3044	3192	*3044
2	BISSONNE	780	1260	1212	1004	1032	784	560	724	592	796
4	BEECHNUT	1040	1552	1172	1012	856	772	788	836	960	1032
6	FONDREN	372	524	476	528	528	456	320	296	312	312
7	BELLAIRE	640	1260	824	1184	224	524	568	568	764	608
9	HILLCROF	444	716	800	780	840	644	904	256	436	700
10	WESTPARK	468	756	1020	800	716	616	732	620	644	644
12	CHIMNEY	524	736	1608	1792	1784	1600	1540	1620	1328	1584
14	I-610	2188	2172	2880	3280	2908	2740	2796	3080	2724	3044
16	NEWCASTL	76	64	132	372	712	996	1152	1080	856	844
19	EDLOE	176	284	416	528	796	984	952	1144	976	680
20	BUFFALO	156	212	284	316	568	880	1064	984	736	740
22	KIRBY DR	84	176	240	324	456	756	600	980	576	816
24	SHEPERD	80	116	180	236	344	480	704	664	656	560
DESTINATION LOCATION		1	2	3	4	5	6	7	8	9	10
3	GESSNER	156	276	540	812	1176	860	788	840	532	564
5	FONDREN	132	304	684	716	600	672	548	520	588	564
8	HILLCROF	240	376	216	120	88	164	380	544	480	524
11	CHIMNEY	212	484	476	404	376	208	228	324	380	628
13	I-610	1772	2700	2512	2508	2340	2136	1892	1840	1840	2092
15	NEWCASTL	104	128	124	144	164	208	244	300	284	328
17	WESLAYAN	212	256	404	572	536	400	404	436	544	496
18	EDLOE	1652	1488	1712	2148	1848	1348	1176	1244	1048	952
21	KIRBY DR	308	380	548	628	568	528	632	772	768	768
23	GREENBRI	748	928	904	644	528	316	596	584	656	884

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Table 32. Entrance/Exit Volume Data for Route 59, Inbound in Houston

			TIME SLICE 1		TIME SLICE 2		TIME SLICE 3		TIME SLICE 4		TIME SLICE 5		TIME SLICE 6		TIME SLICE 7		TIME SLICE 8		TIME SLICE 9		TIME SLICE 10	
	LOCATION	TYPE	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF
1	BISSONNE	M ON	1800		2776		3152		2242		3422		4208		3763		3044		3192		3044	
2	BISSONNE	M ON	780		1260		1051		981		1000		720		704		724		592		796	
3	GESSNER	OFF	-156	.0605	-276	.0684	-440	.1047	-448	.1391	-745	.1685	-760	.1420	-788	.1764	-840	.2229	-532	.1406	-564	.1469
4	BEECHNUT	M ON	1040		1465		1074		987		837		741		948		836		960		1032	
5	FONDREN	OFF	-132	.0381	-299	.0572	-563	.1165	-450	.1196	-415	.0919	-557	.1122	-626	.1353	-520	.1382	-588	.1396	-564	.1309
6	FONDREN	M ON	372		343		464		518		519		447		480		296		312		312	
7	BELLAIRE	M ON	640		480		480		1162		480		480		696		568		764		608	
8	HILLCROF	OFF	-240	.0552	-317	.0562	-160	.0325	-96	.0193	-62	.0121	-133	.0248	-480	.0772	-544	.1324	-480	.1021	-524	.1124
9	HILLCROF	M ON	444		480		481		689		743		480		879		431		436		700	
10	WESTPARK	M ON	468		480		824		711		483		480		577		596		797		644	
11	CHIMNEY	OFF	-212	.0423	-392	.0613	-354	.0857	-296	.0470	-262	.0418	-167	.0270	-234	.0375	-311	.0678	-380	.0697	-628	.1145
12	CHIMNEY	M ON	524		736		1600		1792		1784		1600		755		1221		1744		1504	
13	I-610	OFF	-1772	.3326	-2232	.3313	-2023	.2659	-1986	.2548	-1877	.2411	-2111	.2778	-1877	.2779	-1584	.2980	1840	.2699	-2092	.3248
14	I-610	M ON	2180		2172		2880		3200		2908		2245		2150		2773		2983		3419	
15	NEWCASTL	OFF	-104	.0181	-113	.0169	-186	.0125	-124	.0136	-151	.0171	-193	.0249	-207	.0294	-245	.0367	-251	.0315	-328	.0422
16	NEWCASTL	M ON	36		64		132		372		712		946		1150		1077		853		892	
17	WESLAYAN	OFF	-212	.0371	-224	.0338	-347	.0408	-488	.0523	-509	.0543	-410	.0483	-362	.0455	-385	.0485	-516	.0683	-496	.0595
18	EDLOE	OFF	-1652	.3801	-1306	.2040	-1494	.1834	-1869	.2113	-1826	.2959	-1422	.1761	-1088	.1430	-1049	.1466	-1001	.1245	-959	.1224
19	EDLOE	M ON	176		284		416		528		796		860		937		1125		955		792	
20	BUFFALO	M ON	156		212		284		316		568		756		1048		964		727		843	
21	KIRBY DR	OFF	-308	.0736	-336	.0601	-487	.0663	-560	.0715	-565	.0672	-521	.0629	-575	.0676	-661	.0806	-727	.0833	-799	.0939
22	KIRBY DR	M ON	84		176		248		324		456		590		501		970		618		927	
23	GREENBRI	OFF	-748	.1089	-827	.1523	-819	.1153	-617	.0814	-548	.0661	-339	.0407	-521	.0612	-508	.0597	-618	.0717	-908	.1052
24	SHEPERD	M ON	88		116		180		236		344		480		704		664		656		560	
25	UPSTREAM	THRU	0		0		0		0		0		0		0		0		0		0	

Table 33. Ramp and Mainline Metering Plan, with Associated Queueing and Diversion for Route 59, Inbound in Houston

SUMMARY OF METERING PLAN WITH DIVERSION

TIME SLICE		ENTRANCE LOCATION 1 BISSONNE	2 BISSONNE	4 BEECHNUT	6 FONDREN	7 BELLAIRE	9 HILLCROF	10 WESTPARK	12 CHIMNEY	14 I-610	16 NEWCASTL	19 EDLOE	20 BUFFALO	22 KIRBY DR	24 SHEPERD
1	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	METERING RATE	0.	0.	1485.	343.	480.	480.	480.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	21.	40.	69.	35.	32.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	1.	5.	126.	24.	37.	0.	0.	0.	0.	0.	0.	0.
3	METERING RATE	3152.	1451.	1074.	484.	480.	481.	824.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	156.	36.	40.	40.	88.	69.	86.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	42.	4.	5.	3.	66.	86.	26.	0.	0.	0.	0.	0.	0.	0.
4	METERING RATE	2242.	981.	587.	518.	1162.	689.	711.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	313.	36.	40.	40.	88.	89.	86.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	299.	6.	6.	2.	5.	23.	22.	0.	0.	0.	0.	0.	0.	0.
5	METERING RATE	3422.	1480.	837.	519.	480.	743.	483.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	442.	36.	40.	40.	23.	89.	86.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	186.	8.	5.	2.	1.	24.	58.	0.	0.	0.	0.	0.	0.	0.
6	METERING RATE	4288.	720.	741.	447.	480.	480.	480.	0.	2245.	946.	889.	786.	550.	0.
	QUEUED VEH	156.	36.	40.	40.	32.	53.	54.	0.	93.	12.	28.	28.	40.	0.
	DIVERTED VEH	31.	16.	8.	2.	2.	48.	36.	0.	29.	1.	3.	3.	2.	0.
7	METERING RATE	0.	0.	0.	0.	0.	879.	577.	755.	2159.	1159.	937.	1048.	551.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	44.	86.	34.	184.	12.	28.	28.	40.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	16.	37.	163.	76.	1.	4.	4.	2.	0.
8	METERING RATE	0.	0.	0.	0.	0.	0.	556.	1221.	2773.	1677.	1125.	585.	570.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	36.	164.	180.	12.	28.	28.	40.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	24.	59.	77.	1.	5.	5.	3.	0.
9	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	2963.	853.	985.	727.	618.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	94.	12.	28.	35.	28.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	21.	1.	5.	5.	2.	0.
10	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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Table 34. Geometric and Constraint Data for I-395 (Shirley Highway), Inbound in Virginia

PROBLEM STRUCTURE INPUT DATA

FREEWAY SPEED (MI/HR): 54.
ALTERNATE ROUTE SPEED (MI/HR): 10.
NUMBER OF SECTIONS: 28
NUMBER OF TIME SLICES: 8
DURATION OF EACH TIME SLICE (MIN): 15.
OD DEMAND VOLUME FILE: SHREXT.ODE
TOTAL OD VOLUME MULTIPLIER: 1.0000
RAMP CONSTRAINT OPTION (0 NO CONSTRAINT, 1 WITH CONSTRAINT): 1

	LOCATION	TYPE	MIN RAMP RATE	MAX RAMP RATE	VOL MAX RATE	QUE MAX (VEH)	FREEWAY CAPACITY	SECTION LENGTH	NUMBER OF LANES	AUXILIARY* LANES
1	UPSTREAM	M ON	2000.	8000.	8000.	214.	8000.	0.00		
2	EDSALL S	OFF	0.	0.	0.	0.	6000.	0.19	3	F
3	EDSALL	M ON	240.	900.	1500.	112.	8000.	0.21	3	
4	EDSALL N	OFF	0.	0.	0.	0.	6000.	0.49	3	F
5		THRU	0.	0.	0.	0.	6000.	0.09	3	
6		THRU	0.	0.	0.	0.	6000.	0.36	3	
7	DUKE SB	OFF	0.	0.	0.	0.	6000.	0.28	3	D
8	DUKE NB	OFF	0.	0.	0.	0.	6000.	0.21	3	
9	DUKE	M ON	480.	1800.	3000.	117.	8000.	0.23	3	
10		THRU	0.	0.	0.	0.	8000.	0.49	3	F
11	SEMINARY	OFF	0.	0.	0.	0.	6000.	0.67	3	F
12		THRU	0.	0.	0.	0.	6000.	0.21	3	
13		THRU	0.	0.	0.	0.	6000.	0.12	3	
14	SEMINARY	M ON	240.	900.	1500.	72.	8000.	0.08	3	
15	KING	OFF	0.	0.	0.	0.	6000.	0.47	3	F
16	KING SB	M ON	240.	900.	1500.	39.	6000.	0.20	3	
17	KING NB	M ON	240.	900.	1500.	50.	8000.	0.32	3	A
18	SHIRLING	OFF	0.	0.	0.	0.	6000.	0.21	3	F
19		THRU	0.	0.	0.	0.	6000.	0.36	3	
20	SHIRLING	M ON	480.	1800.	3000.	36.	8000.	0.17	3	
21	GLEBE SB	OFF	0.	0.	0.	0.	6000.	0.15	3	F
22	GLEBE SB	M ON	240.	900.	1500.	24.	8000.	0.12	3	
23	GLEBE NB	OFF	0.	0.	0.	0.	6000.	0.08	3	F
24	DWSTREAM	THRU	0.	0.	0.	0.	8000.	0.25	3	
25	DEST1	OFF	0.	0.	1500.	0.	8000.	1.00	4	
26	DEST2	OFF	0.	0.	0.	0.	8000.	1.00	4	
27	DEST3	OFF	0.	0.	1500.	0.	8000.	1.00	4	
28	DEST4	OFF	0.	0.	0.	0.	8000.	1.00	4	

*A: acceleration lane (nominally 500 feet); D: deceleration lane (nominally 500 feet);
F: full (extends length of this section)

Table 35. Traffic Demand Data for I-395 (Shirley Highway), Inbound in Virginia

ORIGIN LOCATION		VOLUME (VEH/HR)*
1	UPSTREAM	6111
3	EDSALL	711
9	DUKE	1253
14	SEMINARY	720
16	KING SB	346
17	KING NB	495
20	SHIRLINGTON	1391
22	GLEBE SB	344
DESTINATION LOCATION		
2	EDSALL SB	489
4	EDSALL NB	760
7	DUKE SB	724
8	DUKE NB	727
11	SEMINARY	754
15	KING	641
18	HISRLINGTON	276
21	GLEBE SB	465
22	GLEBE NB	131
25	DOWNSTREAM	6404

*This is the peak 15-minute volume. To obtain demand data for each of eight time slices, factors of .8, .8, 1.0, 1.0, .8, .8, .7 and .6 were applied uniformly to all volume data.

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Table 36. Entrance/Exit Volume Data for I-395 (Shirley Highway), Inbound in Virginia

		TIME SLICE 1		TIME SLICE 2		TIME SLICE 3		TIME SLICE 4		TIME SLICE 5		TIME SLICE 6		TIME SLICE 7		TIME SLICE 8	
LOCATION	TYPE	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF	ON/OFF VOL	FR OFF
1 UPSTREAM	M ON	4889		4889		6888		6888		5111		4889		4278		3667	
2 EDSALL S	OFF	-391	.0800	-391	.0800	-488	.0800	-488	.0800	-489	.0800	-391	.0800	-342	.0800	-293	.0800
3 EDSALL	M ON	569		569		488		488		860		569		498		427	
4 EDSALL N	OFF	-600	.1200	-600	.1200	-720	.1200	-707	.1179	-633	.1137	-600	.1200	-532	.1200	-456	.1200
7 DUKE SB	OFF	-579	.1299	-579	.1299	-686	.1299	-688	.1299	-683	.1222	-579	.1299	-507	.1299	-434	.1299
8 DUKE NB	OFF	-582	.1499	-582	.1499	-689	.1499	-690	.1499	-685	.1398	-582	.1499	-509	.1499	-436	.1499
9 DUKE	M ON	1002		1002		1253		1067		1168		1002		877		752	
11 SEMINARY	OFF	-603	.1403	-603	.1403	-724	.1403	-702	.1403	-686	.1403	-603	.1403	-528	.1403	-452	.1403
14 SEMINARY	M ON	576		576		694		368		860		580		504		432	
15 KING	OFF	-513	.1200	-513	.1200	-615	.1200	-568	.1200	-574	.1132	-513	.1200	-449	.1200	-385	.1200
16 KING SB	M ON	277		277		240		269		262		433		242		208	
17 KING NB	M ON	396		396		264		474		376		596		347		297	
18 SHIRLING	OFF	-221	.0498	-221	.0498	-250	.0498	-232	.0478	-230	.0448	-221	.0461	-193	.0498	-166	.0498
20 SHIRLING	M ON	1113		1113		1233		1381		1100		1257		974		835	
21 GLEBE SB	OFF	-372	.0699	-372	.0699	-419	.0699	-401	.0668	-375	.0625	-372	.0639	-326	.0699	-279	.0699
22 GLEBE SB	M ON	275		275		344		344		275		275		241		206	
23 GLEBE NB	OFF	-105	.0200	-105	.0200	-119	.0200	-114	.0192	-108	.0183	-105	.0183	-92	.0200	-79	.0200

Table 37. Ramp and Mainline Metering Plan, with Associated Queueing and Diversion for I-395 (Shirley Highway), Inbound in Virginia

SUMMARY OF METERING PLAN
WITH DIVERSION

TIME SLICE		ENTRANCE LOCATION 1 UPSTREAM	3 EDSALL	9 DUKE	14 SEMINARY	16 KING SB	17 KING NB	20 SHIRLING	22 GLEBE SB
1	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.
2	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.
3	METERING RATE	6000.	480.	0.	694.	240.	264.	1233.	0.
	QUEUED VEH	28.	51.	0.	6.	25.	50.	36.	0.
	DIVERTED VEH	0.	7.	0.	0.	1.	8.	3.	0.
4	METERING RATE	6000.	480.	1087.	368.	269.	474.	1381.	0.
	QUEUED VEH	56.	73.	42.	72.	39.	50.	36.	0.
	DIVERTED VEH	0.	36.	0.	22.	5.	5.	2.	0.
5	METERING RATE	0.	0.	0.	860.	262.	376.	1100.	0.
	QUEUED VEH	0.	0.	0.	1.	39.	50.	36.	0.
	DIVERTED VEH	0.	0.	0.	0.	4.	5.	3.	0.
6	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.
7	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.
8	METERING RATE	0.	0.	0.	0.	0.	0.	0.	0.
	QUEUED VEH	0.	0.	0.	0.	0.	0.	0.	0.
	DIVERTED VEH	0.	0.	0.	0.	0.	0.	0.	0.

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6.3 Design of Experiments

There is a need for quantitative predictions of the degree of success of redesign and/or control as qualitatively described in the previous section 2.3. A design of experiment is proposed in which a simulation model would be employed for such predictions.

The base simulation run would be made of a hypothetical "typical" section of freeway (upstream, within, and downstream of an interchange) under existing conditions without control. Variations in the supply side (number and spacing of ramps, freeway lane configurations, etc.), the demand side (the O-D demand level, trip length distribution, etc.) and the control features (allowable metering rates, pre-set ramp control, etc.) would be examined.

The design of experiment would follow the process described earlier in the section 2.3.

6.3.1 Downstream of Interchange

Referring to Table 2 as a starting point, the design of experiment might be as indicated in Table 38:

6.3.2 Upstream of Interchange

Referring to Table 3 as a starting point, the design of experiment may be as indicated in Table 39. The base run for this sequence would be selected cells from Table 38 and might include cells 1-3, 10-12, 19-21, 29-30, 5-6, 14-15, and 32-33. The numerical results from these cell investigations would further reduce the number of base conditions carried forward.

6.3.3 Interchange Subsystem

Referring to Table 4 as a starting point, and considering the results of production runs shown in Tables 38 and 39, a design of experiment could be formulated. Only investigations which have not been solved effectively in upstream and downstream design/control need be examined. The main variables to be considered would be the demand pattern of the interchange roadways and their lane configuration.

Table 38. Treatment Downstream of Interchange

REDESIGN SOLUTION				NO REDESIGN (EXISTING CONGESTION)		PARTIAL REDESIGN (SOME CONGESTION)		FULL REDESIGN (NO CONGESTION)	
ALTERNATE ROUTES				GOOD	POOR	GOOD	POOR	GOOD	POOR
D/C AT BOTTLENECK	1.05	NUMBER OF ON-RAMPS	0	1	10	19	28	37	46
	1.10		0	2	11	20	29	38	47
	1.20		0	3	12	21	30	39	48
	1.05		3	4	13	22	31	40	49
	1.10		3	5	14	23	32	41	50
	1.20		3	6	15	24	33	42	51
	1.05		10	7	16	25	34	43	52
	1.10		10	8	17	26	35	44	53
	1.20		10	9	10	27	36	45	54

Table 39. Treatment Upstream of Interchange

		ALTERNATE ROUTES	
		GOOD	FAIR
PERCENT UPSTREAM TRAFFIC TRAVELLING TO DOWNSTREAM BOTTLENECK	67	A	D
	75	B	E
	90	C	F

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APPENDIX A

SUMMARY OF FREEWAY TO FREEWAY RAMP CONTROL INSTALLATIONS

Prepared for the

Transportation Research Board - Freeway Operations Committee
Committee No. A3A09

Prepared by — Mr. Glen C. Carlson, P.E.
Manager, Traffic Management Center
Mn/DOT, Office of Traffic Engineering

and — Mr. Stuart H. Harvey, P.E.
District Traffic Engineer - Systems
CALTRANS, District 11 (San Diego)

Reviewed by — Members of the Traffic Management Task Group of the Freeway Operations Committee

for the T.R.B. 60th Annual Meeting

January 12-16, 1981 in Washington, D.C.

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TABLE OF CONTENTS

	PAGE
INTRODUCTION	1
PROJECT DESCRIPTIONS	2
Interchanges	
Routes 15 and 94 in San Diego, CA	3
I-805 and Route 94 in San Diego, CA	6
Routes 94 and 125 in San Diego, CA	8
I-35E and T.H. 36 in Little Canada, MN	10
I-94 and I-35W in Minneapolis, MN	13
I-494 and I-35W in Bloomington, MN	16
I-35W and T.H. 13 in Burnsville, MN	20
CONCLUSIONS	23

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INTRODUCTION

One of the objectives for the Traffic Management Task Group of the T.R.B. Freeway Operations Committee is to compile information on in-place freeway to freeway ramp control systems. Committee members and others involved in freeway traffic management were requested to submit descriptions of freeway to freeway metering projects that they are responsible for. This report summarizes the responses to this request, providing an overview of the inplace systems, an analysis of the operational experience of these systems, and general conclusions.

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PROJECT DESCRIPTIONS

Information on freeway to freeway ramp metering at three interchanges in San Diego and four interchanges in the Minneapolis-St. Paul Metropolitan Area is presented in this section. A separate summary is presented for each interchange, including information on the following:

- The interchange location and specific ramps metered.
- A description of the metering location including the type of interchange, number of lanes on the intersecting freeways, and details of channelization for queue storage or preferential treatment for high occupancy vehicles (HOVs).
- Ramp metering details including the type of control, turn-on logic, provisions for HOVs, and signal and signing hardware.
- Data on ramp volumes and vehicle delays at the metered ramps.
- A brief operational analysis including information on improvements to traffic flow, enforcement experience, public reaction, and any difficulties experienced.

In addition to the above, a layout showing interchange geometrics and hardware location is presented for each project.

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Interchange of Routes 15 and 94

Agency: California Department of Transportation

Location: Ramps from NB (loop) and SB Route 15 to WB Route 94 in San Diego.

Description of Freeways: Route 15 is a four-lane freeway and Route 94 is an eight-lane freeway. The interchange is a typical cloverleaf except that the WB to SB ramp is a left-lane exit connection. The SB to WB metered connection has been widened to two lanes to provide for a preferential lane for carpools.

Ramp Control Information: The SB and WB connection has been metered since October, 1971. In May, 1978 that location became part of an extensive system of ramp control utilizing type 170 controllers. The NB to WB loop was first controlled in May, 1978.

The metering operation (turn-on, turn-off, and rate selection) is entirely traffic responsive, being a function of main line occupancy. Controllers are connected by telephone line to a central office which provides second-level supervision over the system.

Signal and signing hardware are as shown in Figure 1. Advance warning on the loop ramp consists of a "SIGNAL AHEAD" symbol sign with a "RAMP SIGNAL" supplemental plate and an eight inch yellow flashing beacon. The beacon is energized during the metering period. Advance warning on the SB to WB ramp consists of an internally illuminated, extinguishable message sign with flashing beacons. The message reads "RAMP METERED - STOP AHEAD". Metering is initiated with steady green followed by a 5.0 second yellow. There are 15 cycle lengths available, ranging from 7.1 to 13.7 seconds on the loop, and from 7.5 to 18.0 seconds on the leg.

On the loop ramp, one vehicle per green is discharged. On the SB to WB ramp, two vehicles per green are discharged. The preferential lane is also metered, but at an independent rate. Signal heads are dark outside the peak period.

Ramp Volumes and Delays:

The loop ramp volume is quite low - 150 VPH. Metering was installed, in part, to protect against diversion from other, high volume ramps. Delay is on the order of five to ten seconds. The SB to WB ramp volume is 800 VPH. Average delay is about one minute, and maximum delay is about three minutes. Queue lengths occasionally exceed 750 feet but cause no interference with route 15 southbound through traffic.

Operational Analysis:

Ramp entrance control at this interchange has accomplished all it was intended to:

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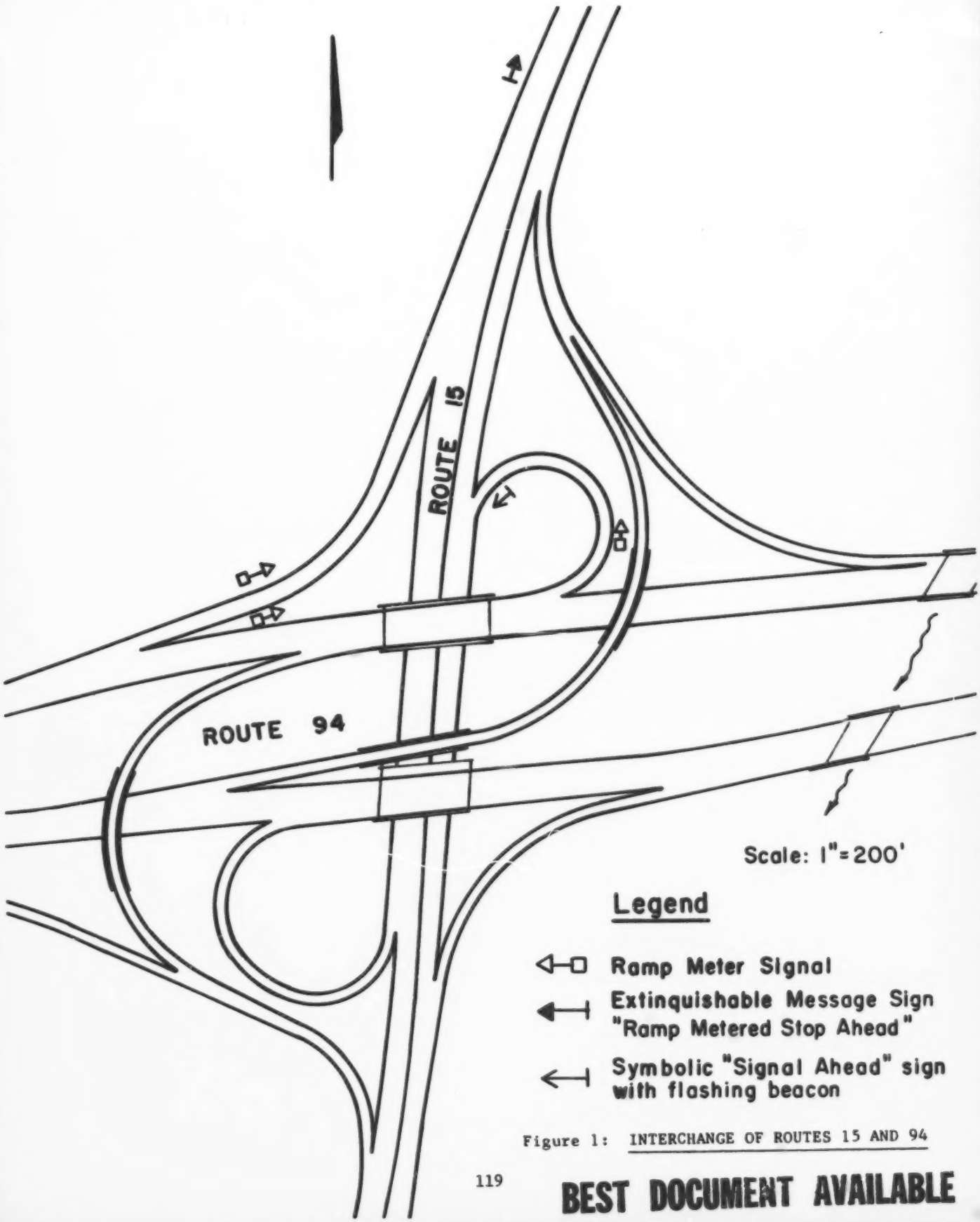

Figure 1: INTERCHANGE OF ROUTES 15 AND 94

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- As part of a system of meters it has restored free flow to Route 94;
- Adverse reaction from the public has been rare;
- Compliance is at an acceptable level, although violation of the minimum occupancy level in the preferential lane requires occasional enforcement effort. There have been no accidents associated with the metering operation.

Metering of the carpool lane has provided a distinct benefit; enforcement of the minimum occupancy level is greatly facilitated. An officer can wave over violators as they are stopped at the meter, and cite them on the spot. No chase onto the freeway is necessary. Often two or more violators may be stopped at once. Disadvantages of metering the preferential lane are not significant; since the queue in that lane is always short, delay of HOVs is only a few seconds.

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Interchange of I-805 and Route 94

Agency: California Department of Transportation

Location: Direct connection from NB I-805 to WB Route 94 in San Diego.

Description of Freeways: Route 805 and Route 94 are each eight-lane freeways. The interchange is a three-level facility. The NB to WB connection has two lanes, one of which is reserved for carpools during the morning peak period.

Ramp Control Information: The NB to WB connection has been metered since May, 1978. It is part of an extensive system of ramp control utilizing Type 170 controllers.

The metering operation (turn-on, turn-off and rate selection) is entirely traffic responsive, being a function of main lane occupancy. Controllers are connected by telephone line to a central office which provides second-level supervision over the system.

Figure 2 shows the ramp meter and advance warning sign locations. Advance warning consists of an overhead internally illuminated extinguishable message sign which reads, "PREPARE TO STOP."

Metering is initiated with a steady green followed by a 5.0 second yellow. There are 15 cycle lengths available, ranging from 7.1 to 9.7 seconds. Two vehicles per green are discharged. The preferential lane for carpools is also metered, but at an independent rate. Signal heads are dark outside the peak period.

Ramp Volumes and Delays:

The ramp volume is about 1450 VPH during the peak period. Average delay is about 70 seconds, and maximum delay is about two minutes.

Operational Analysis:

See the comments for the Route 94/15 interchange.

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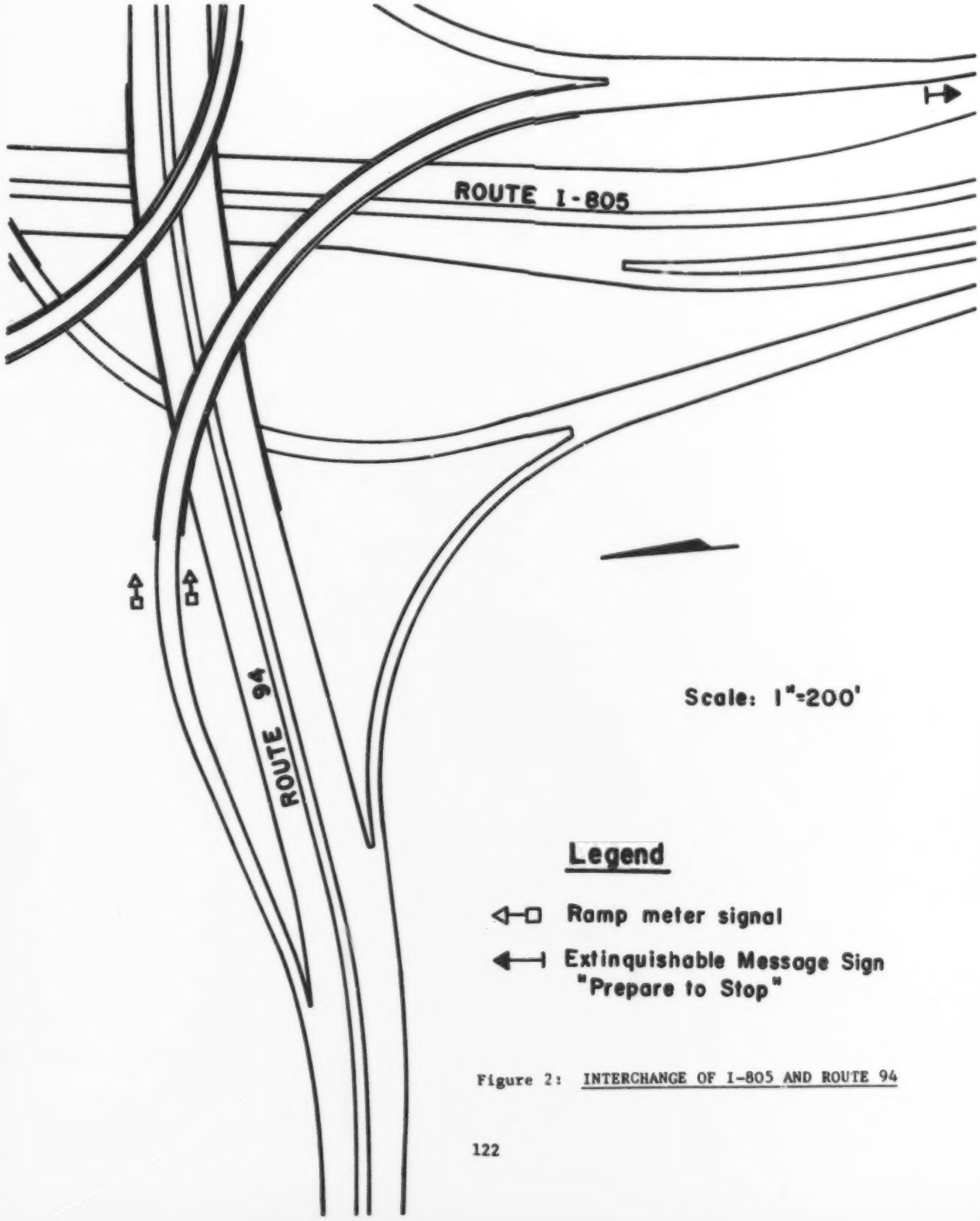

Figure 2: INTERCHANGE OF I-805 AND ROUTE 94

Interchange of Routes 94 and 125

Agency: California Department of Transportation

Location: Direct connection for WB traffic at the Route 94/125 interchange in San Diego.

Description of Freeways: Route 94 has four to six lanes, and Route 125 has four lanes. The interchange has a wye configuration, with Route 94 swinging from north - south to east - west at this point. The westbound Route 94 connector is three lanes wide. During metering the inside (driver's left) lane is reserved for buses and carpools. At other times that lane is not used.

Ramp Control Information: This location has been metered since May, 1978, and is part of an extensive system of ramp control utilizing Type 170 controllers.

The metering operation (turn-on, turn-off and rate selection) is entirely traffic responsive, being a function of main lane occupancy. Controllers are connected by telephone line to a central office which provides second-level supervision over the system.

Ramp meter and advance warning sign locations are shown in Figure 3. Advance warning consists of two overhead internally illuminated extinguishable message signs which read, "PREPARE TO STOP." The first is 2,400 feet in advance and the second is 1,300 feet in advance of the meter.

Metering is initiated with a steady green followed by a 5.0 second yellow. There are 15 cycle lengths available, ranging from 7.3 to 9.2 seconds. Two vehicles are discharged in each lane during each green cycle. The two mixed flow lanes operate together; the carpool lane is metered separately with simultaneous greens prevented. Signal heads are dark outside the metering period.

Ramp Volume and Delays: The ramp volume is about 1900 VPH during the peak period. Average delay is about one minute, and maximum delay is about three minutes.

Operation Analysis:

See the comments for the Route 94/15 interchange.

Note - for additional information on any of the Caltrans projects, please contact Mr. Stuart Harvey at the following address: Caltrans - District 11, P.O. Box 81406, San Diego, California 92138 (phone no. 714-237-6895).

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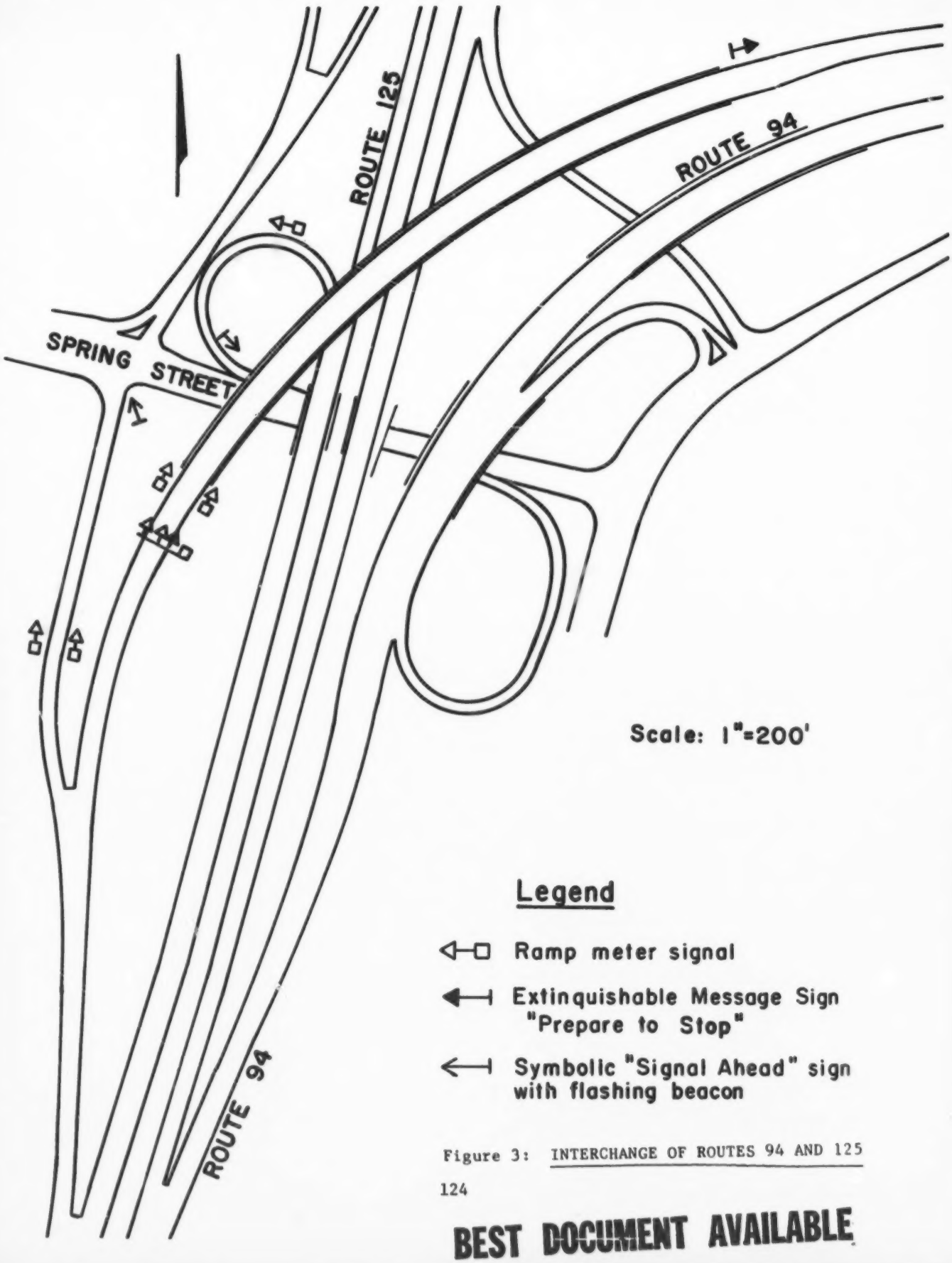

Figure 3: INTERCHANGE OF ROUTES 94 AND 125

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Interchange of I-35E and T.H.* 36

Agency: Minnesota Department of Transportation

Location: Ramps from EB (leg) and WB (loop) T.H. 36 to SB I-35E in Little Canada.

Description of Freeways: I-35E is a six-lane freeway at this location, which is about four miles north of the St. Paul CBD. T.H. 36 is a four-lane expressway which was constructed to freeway standards for a distance of seven miles to the east and four miles to the west of this interchange. The interchange is a cloverleaf type, without frontage roads. The advisory speed limit for the EB to SB leg is 40 mph.

Ramp Control Information: Ramp metering was activated at these ramps in November, 1971 as part of a six-ramp system on SB I-35E. The control is isolated, traffic-adjusted utilizing controllers designed and assembled by state forces. Vehicles are released one at a time, single file, at cycle lengths of 5.5, 6.5, and 8.0 seconds. Cycle lengths are selected according to flow conditions on the mainline, as measured by a lane occupancy unit in the control cabinet. The controller has gap seeking capability for system start up each A.M. peak period, but has no queue detection or override capability. Meter turn-on logic functions as follows:

1. Flashing yellow at one-half voltage during the non-metering period.
2. Changes to steady green at 7:00 A.M.
3. When a 6.0 second gap is found (travel time from gap detector to stop line), the steady green changes to steady yellow for 3.5 seconds, and then to steady red. This is followed by normal green-yellow-red cycling.

Signal and signing hardware locations are as shown in Figure 4. The signals are standard three-section eight inch heads, mounted on five foot pedestals. Advanced warning is provided via an amber bulb-matrix type sign with the message "METERED", mounted above the standard exit gore signs. The letter height on the "METERED" sign is 12 inches, and the sign is flashed whenever the meters are operating, and dark at all other times. The symbolic "SIGNAL AHEAD" signs are the standard 36 inch by 36 inch signs described in the MUTCD.

Ramp Volumes and Delays: Prior to the implementation of ramp control the A.M. peak hour volumes were 610 on the EB to SB leg, and 560 on the WB to SB loop. Current peak hour volumes are 520 on the leg, and 450 on the loop, and average vehicle delays during the peak hour are 0.7 minutes on the leg, and 0.2 minutes on the loop. Queue lengths do not normally extend beyond the ramp entrances.

* T.H. = Trunk Highway (State Highway)

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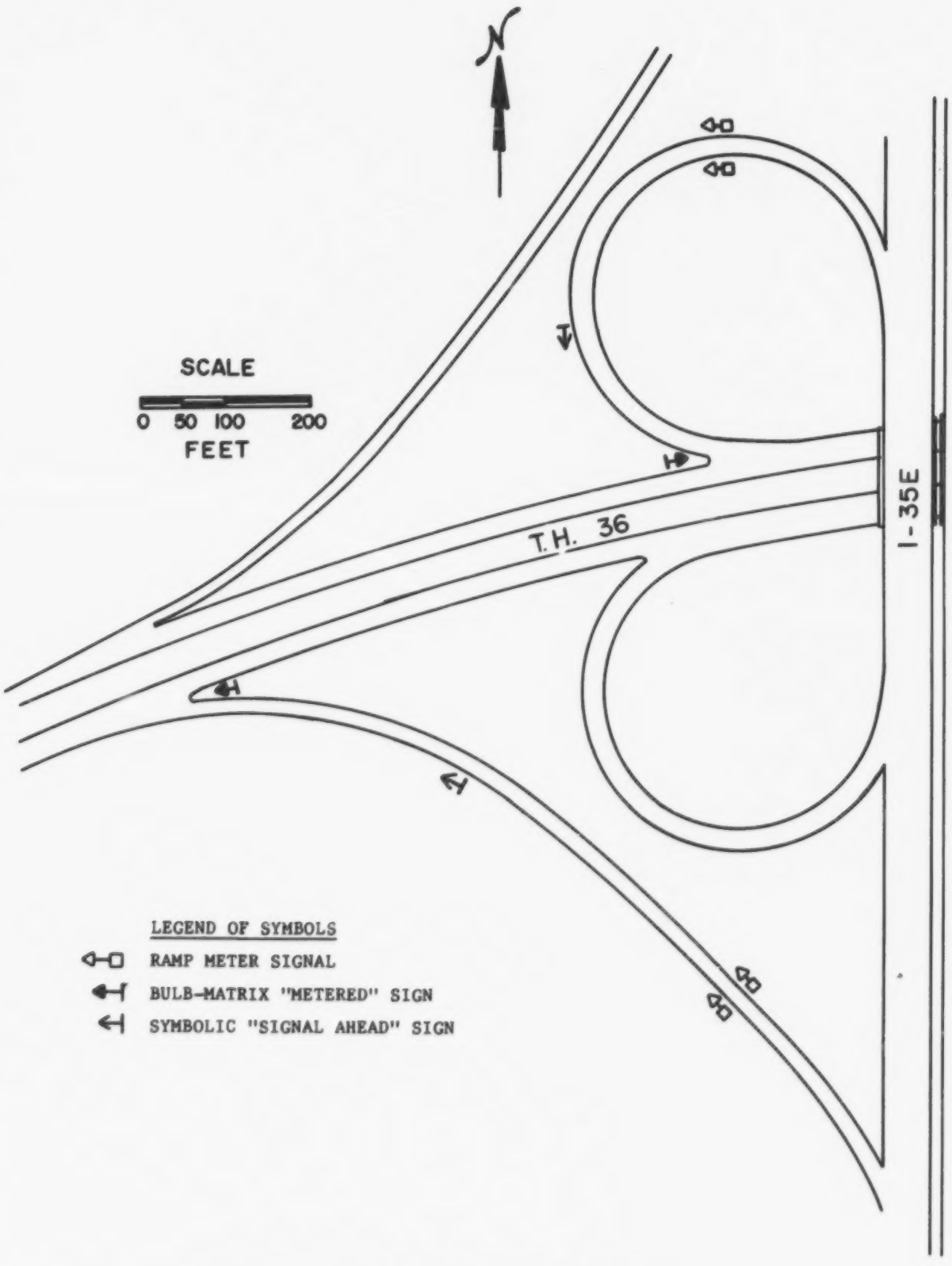

Figure 4 : INTERCHANGE OF I-35E and T.H. 36

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Operational Analysis: These ramps have been successfully metered for over eight years, contributing significantly to the following benefits on SB I-35E.

- Peak hour freeway speeds have averaged 16 percent higher than speeds measured prior to system implementation.
- Peak hour accidents have been reduced by 37 percent, comparing two years of experience prior to system implementation to eight years with the system in operation.

Driver acceptance of these ramp control signals has been quite high as reflected by the 99 percent compliance rate, and low number of complaints (averaging about two per year).

Operational difficulties have been encountered on a few occasions during snow storms. Maintenance forces are sometimes unable to prevent icy conditions on these uphill ramps, and in these situations the meters are manually placed in flashing operation by the State Patrol.

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Interchange of I-94 and T.H. 65

Agency: Minnesota Department of Transportation

Location: Ramps from EB I-94 to SB T.H. 65 (freeway connector to SB I-35W) in Minneapolis.

Description of Freeways: T.H. 65 is a four-lane freeway which leads to an eight-lane section of I-35W at this location on the southeast edge of downtown Minneapolis, and I-94 is a six-lane freeway. The metered ramp is a right lane exit from I-94 and right lane entrance to T.H. 65 with an advisory speed limit of 35 mph.

Ramp Control Information: Ramp metering was activated at this ramp in June, 1974 as part of the I-35W Urban Corridor Demonstration Project (U.C.D.P.) on a 17 mile section of freeway south of the Minneapolis CBD. This system is computer controlled, utilizing six cycle lengths at each ramp selected according to mainline flow conditions. There are two lanes approaching the meter, and two vehicles are released simultaneously on each green interval (one from each lane). Meter turn-on logic functions as follows:

1. Flashing yellow at one-half voltage during non-metering period.

2. Changes to steady green when P.M. peak period mainline traffic reaches the threshold level. A time clock constraint prevents this change from occurring prior to 3:00 P.M., but automatically activates the change at 3:30 P.M. if it hasn't occurred earlier.

3. When a 6.0 second gap is found (travel time from queue/gap detector to stop line), the steady green changes to steady yellow for 3.0 seconds, and then to steady red. This is followed by normal green-yellow-red operation at cycle lengths ranging from 5.3 to 15.0 seconds.

Signal and signing hardware locations are as shown in Figure 5. The signals and advance warning "METERED" sign are the same as those used at the interchange of I-35E and T.H. 36, and were described earlier. The symbolic "SIGNAL AHEAD" sign is the standard 36 inch by 36 inch sign described in the MUTCD.

Ramp Volumes and Delays: Prior to the implementation of ramp control the P.M. peak hour volume on this ramp was 1,080, and the current peak hour volume is 690. The average vehicle delay on this ramp is a little over one minute during the peak hour. The two lane storage helps shorten queue lengths, however, on some occasions the queue length reaches over one-quarter mile upstream from the meter, resulting in maximum delays of approximately eight minutes.

It is estimated that over two-thirds of the peak hour volume reduction at this ramp may be attributed to diversion to alternate routes. This is typical for the freeway to freeway ramp meters operated by Mn/DOT.

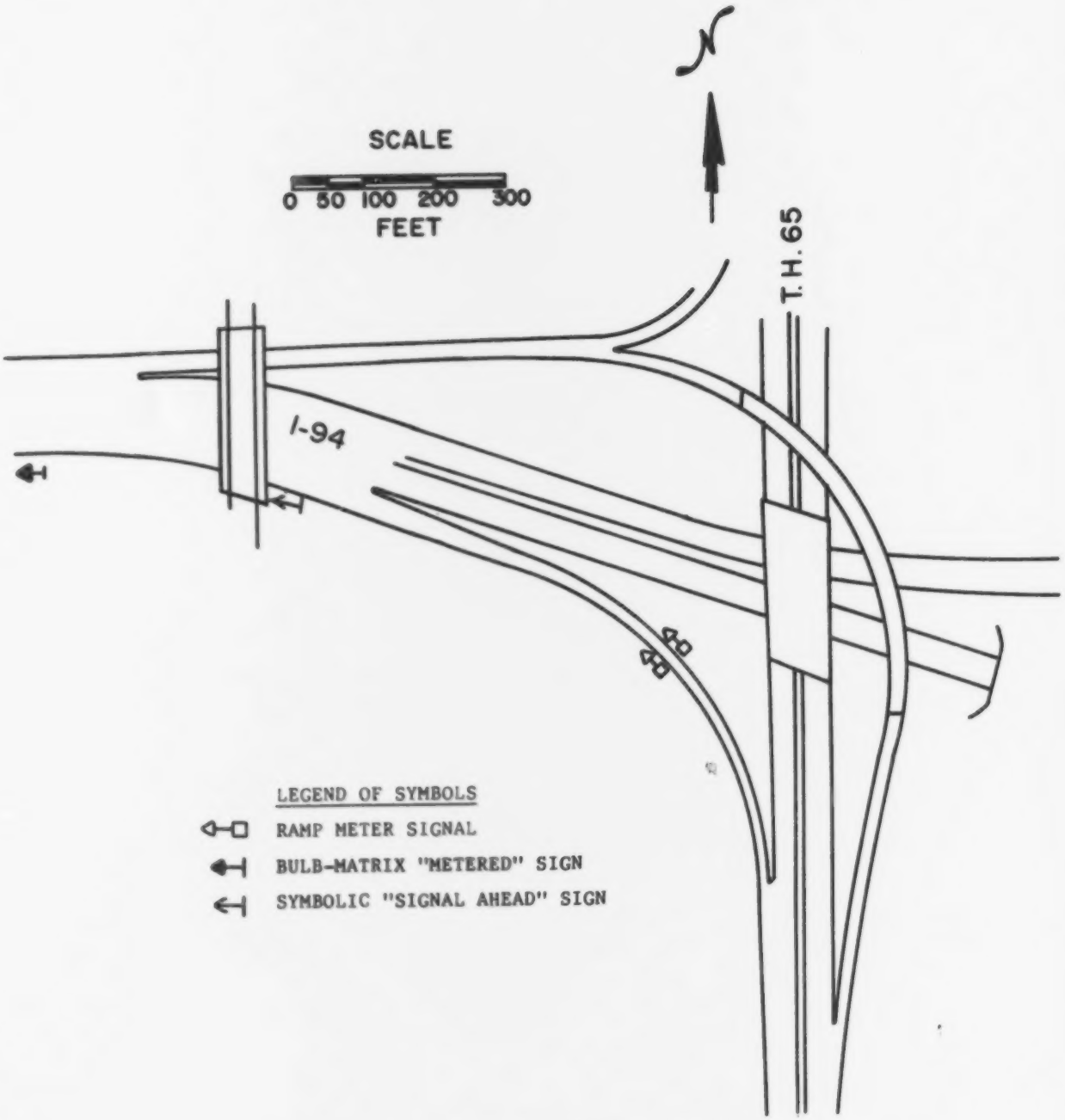

Figure 5: INTERCHANGE OF I-94 AND T.H. 65

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Operational Analysis: This ramp has been metered without major problems for over six years. At certain times, usually when a major incident occurs downstream, excessive queuing has caused some concern. The queue is stored along an auxiliary lane which is over 3,000 feet long, so traffic does not stop on the mainline and accidents are not a problem. However, some motorists have indicated that they are apprehensive about waiting in the queue when freeway traffic is passing them in the adjacent lane.

Ramp control at this location is essential to management of downstream conditions, and the metering has contributed significantly to the following benefits:

- Southbound peak hour freeway speeds have averaged 29 percent higher than speeds measured prior to system implementation.
- Peak period accidents have been reduced by 21 percent, comparing two years of experience prior to system implementation to five years experience with the system in operation.

These improvements have been achieved even though peak period freeway volumes increased by 17 percent during the years studied.

Interchange of I-494 and I-35W

Agency: Minnesota Department of Transportation

Location: Ramps from EB (leg) and WB (loop) I-494 to SB I-35W, and from WB (leg) and EB (loop) I-494 to NB I-35W in Bloomington.

Description of Freeways: I-494 is a six-lane circumferential freeway, and I-35W is a four-lane radial freeway. The interchange is a typical cloverleaf type, except that the EB to SB leg has been widened to permit two lanes of storage, and the deceleration lane leading to this ramp has been lengthened to permit additional storage. The advisory speed limit on both legs is 40 mph.

Ramp Control Information: Metering was activated at these four ramps in November 1975 as an expansion of the I-35W U.C.D.P., increasing the number of metered ramps to 38. Three of the ramps have single lane storage at the meter, and release one vehicle per green interval. The fourth, the EB to SB leg, has two lanes approaching the meter, and releases one vehicle per green interval on an alternate basis. Computer control of metering rates and turn-on logic are the same as described earlier for the interchange of I-94 and T.H. 65, except that longer gaps are needed during the initial green intervals. This is necessary because the travel times from the queue/gap detectors to the stop lines are longer, ranging from 8.0 to 11.0 seconds. Cycle lengths range from 5.3 to 11.0 seconds on all ramps, except the EB to SB leg which releases vehicles (alternately) every 3.6 to 8.6 seconds. Signal and signing hardware locations are as shown in Figures 6 and 7. The signals for the three single lane ramps are standard three-section, eight inch heads, mounted on five foot pedestals. On the EB to SB two lane ramp, ten foot pedestals are used with two standard three-section, eight inch signal heads on each one. One of these signals is mounted at a height of five feet and directed toward vehicles waiting close to the stop line, and the other signal is mounted at a height of ten feet and directed toward the ramp entrance. A sign on each pedestal with the message "LEFT (or RIGHT) LANE SIGNAL" is used to ensure motorist understanding of the alternate green intervals for the two lanes. The symbolic "SIGNAL AHEAD" signs are the standard 36 inch by 36 inch signs described in the MUTCD. The flashers are eight inch yellow signals mounted on top of ten foot pedestals. They flash when the meters are operating, and are dark at all other times.

Ramp Volumes and Delays: Ramp volumes before and after implementation of ramp control, and vehicle delays are shown in the table below.

Ramp	Peak Hour Volume		Average Peak Hour Delay (Minutes)
	Before	After	
EB to SB	1,150	880	1.4
WB to SB	710	520	0.7
EB to NB	600	580	0.7
WB to NB	500	400	0.8

Queuing on the ramps entering NB I-35W causes no problems, however, on the ramps entering SB I-35W queue lengths occasionally extend beyond the ramps and upstream on the shoulder of the intersecting freeway.

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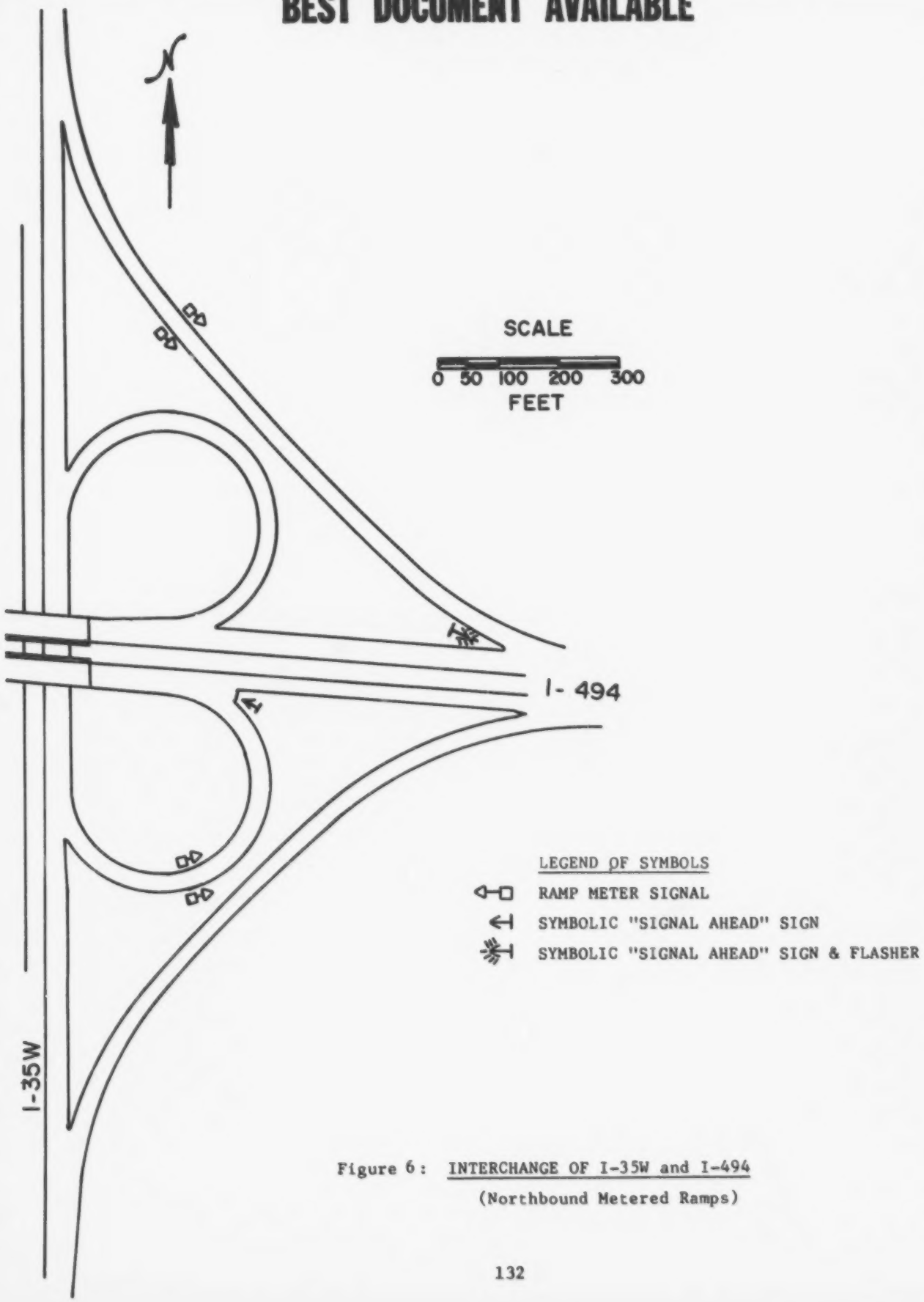

Figure 6: INTERCHANGE OF I-35W and I-494
(Northbound Metered Ramps)

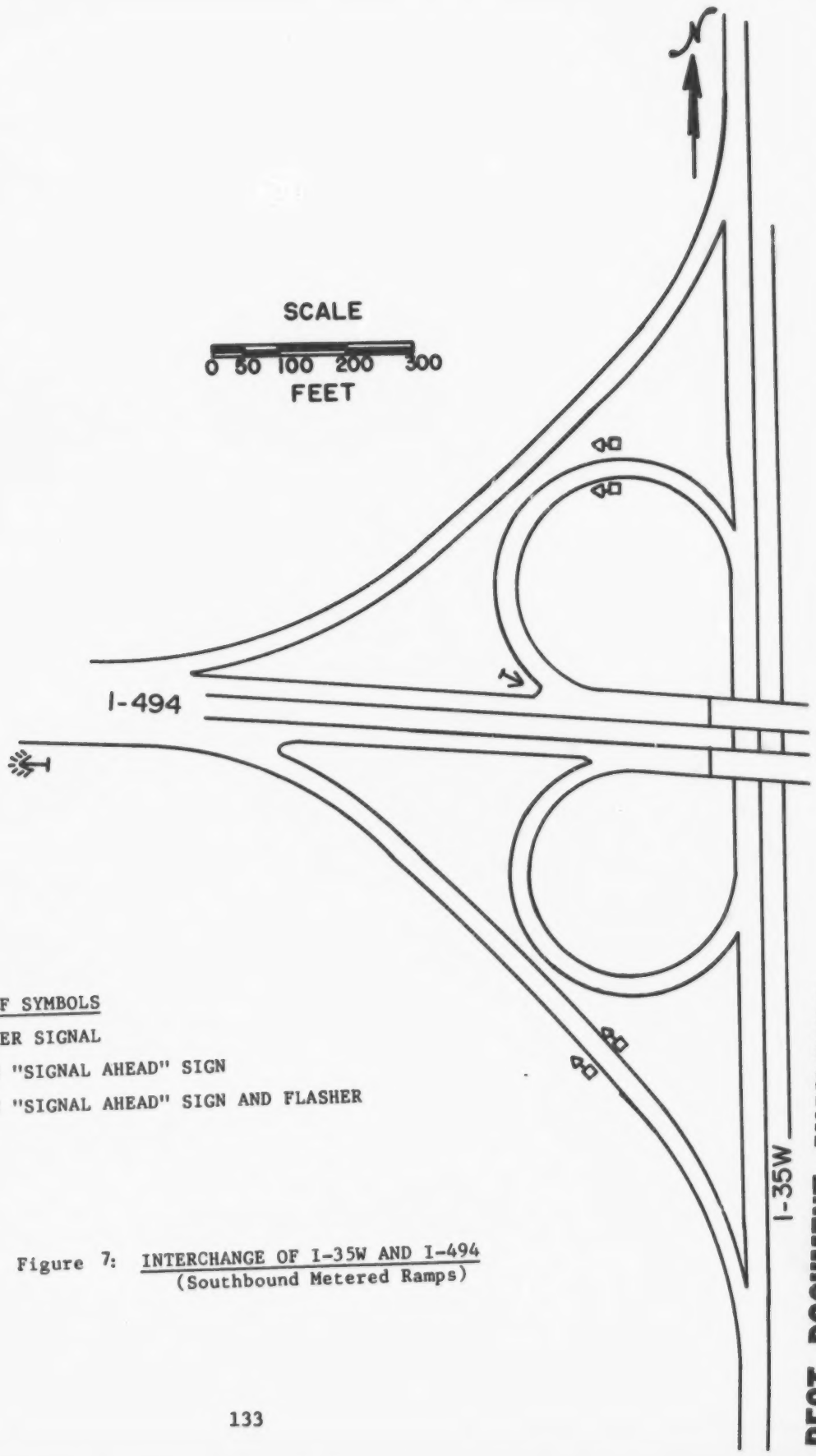

Figure 7: INTERCHANGE OF I-35W AND I-494
(Southbound Metered Ramps)

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Operational Analysis: The ramps entering NB I-35W have been metered successfully during A.M. peak periods with virtually no problems. However, there have been problems during P.M. peak periods on the ramps entering SB I-35W, and following is a brief description of these problems.

The EB to SB leg was originally a single lane ramp, and the queues frequently extended over one-half mile from the meter. The queue would be stored along an auxiliary lane of I-494 which extended from Penn Avenue to I-35W, a distance of about one-half mile. This caused problems for vehicles using the Penn Avenue entrance ramps onto EB I-494. Occasionally the queue would extend beyond Penn Avenue along the shoulder of I-494, and impatient drivers trying to bypass the queue and "cut in" would sometimes slow down or even stop in the right lane of I-494. This problem was greatly alleviated in July, 1979 when the ramp was widened to two lanes and the deceleration lane was lengthened to permit additional storage.

The WB to SB loop experiences heavy platooning which occasionally causes the queue to extend thru the accel-decel lane of the cloverleaf, and back along the shoulder of I-494. System operators attempt to monitor this ramp closely and override the meter to a faster rate when this happens, but sometimes it happens so fast that it is difficult to prevent. Mn/DOT staff considers this ramp to be the most troublesome freeway to freeway metering installation currently in operation.

Despite the problems described above, it is absolutely essential to meter the I-494 ramps to provide an acceptable level of service on I-35W. Ramp control at this interchange has contributed significantly to a 38 percent increase in peak hour speeds on NB I-35W, in addition to the increase in SB speeds and overall reduction in peak period accidents described earlier.

Interchange of I-35W and T.H. 13

Agency: Minnesota Department of Transportation

Location: Ramps from EB (loop) and WB (leg) T.H. 13 to NB I-35W in Burnsville.

Description of Freeways: I-35W is a four-lane freeway at this location, which is about 14 miles south of downtown Minneapolis. T.H. 13 is a four-lane expressway, constructed to freeway standards for a distance of three miles to the west and one-half mile to the east of this typical cloverleaf interchange. The WB to NB leg has an advisory speed limit of 45 mph, and includes an HOV bypass ramp connecting the east frontage road with a ramp location downstream from the meter.

Ramp Control Information: Metering was activated at these ramps in April, 1974 as part of the I-35W U.C.D.P. Both ramps have single lane storage at the meter, and release one vehicle per green interval. Computer control, metering rates, and turn-on logic are the same as described earlier for the other I-35W locations. Buses and carpool vehicles (three person minimum) are permitted to use the bypass ramp. They are detected by loop detectors as they enter the HOV ramps, and the meter is pre-empted to a dwell red until they have bypassed it.

Signal and signing hardware locations are shown in Figure 8. The signals are standard three-section, eight inch heads, mounted on five foot pedestals. The symbolic "SIGNAL AHEAD" signs and flashers are the same as those described for the interchange of I-35W and I-494. Cycle lengths at this location range from 6.0 to 20.0 seconds on the WB to NB loop, and from 5.3 to 15.0 seconds on the EB to NB leg.

Ramp Volumes and Delays: Prior to the implementation of metering the A.M. peak hour volumes were 690 on the EB to NB loop, and 530 on the WB to NB leg. Current peak hour volumes are 520 on the loop, and 410 on the leg. Average vehicle delays during the peak hour are currently about three minutes on the loop, and four minutes on the leg.

Operational Analysis: Queuing and vehicle delays at this location have varied widely depending on the status of the alternate routes. The only alternate routes available are via the bridges crossing the Minnesota River about two miles north of T.H. 13. There were three routes available when the system was activated in 1974, but one of these was permanently closed in February, 1977. Another bridge was closed in May, 1976 and reopened in December, 1977. The third alternate route is via an old, narrow two-lane bridge which is closed occasionally when it is hit by trucks or barges. A new bridge, designed to freeway standards, is currently under construction at this location, and should alleviate the problems at the metered ramps.

Under the worst conditions, the queuing at the T.H. 13 ramps has extended almost a mile upstream from the meters, with peak hour delays of about 14 minutes on the leg and eight minutes on the loop. The queues are stored along the shoulders of the intersecting highway. Volumes are relatively

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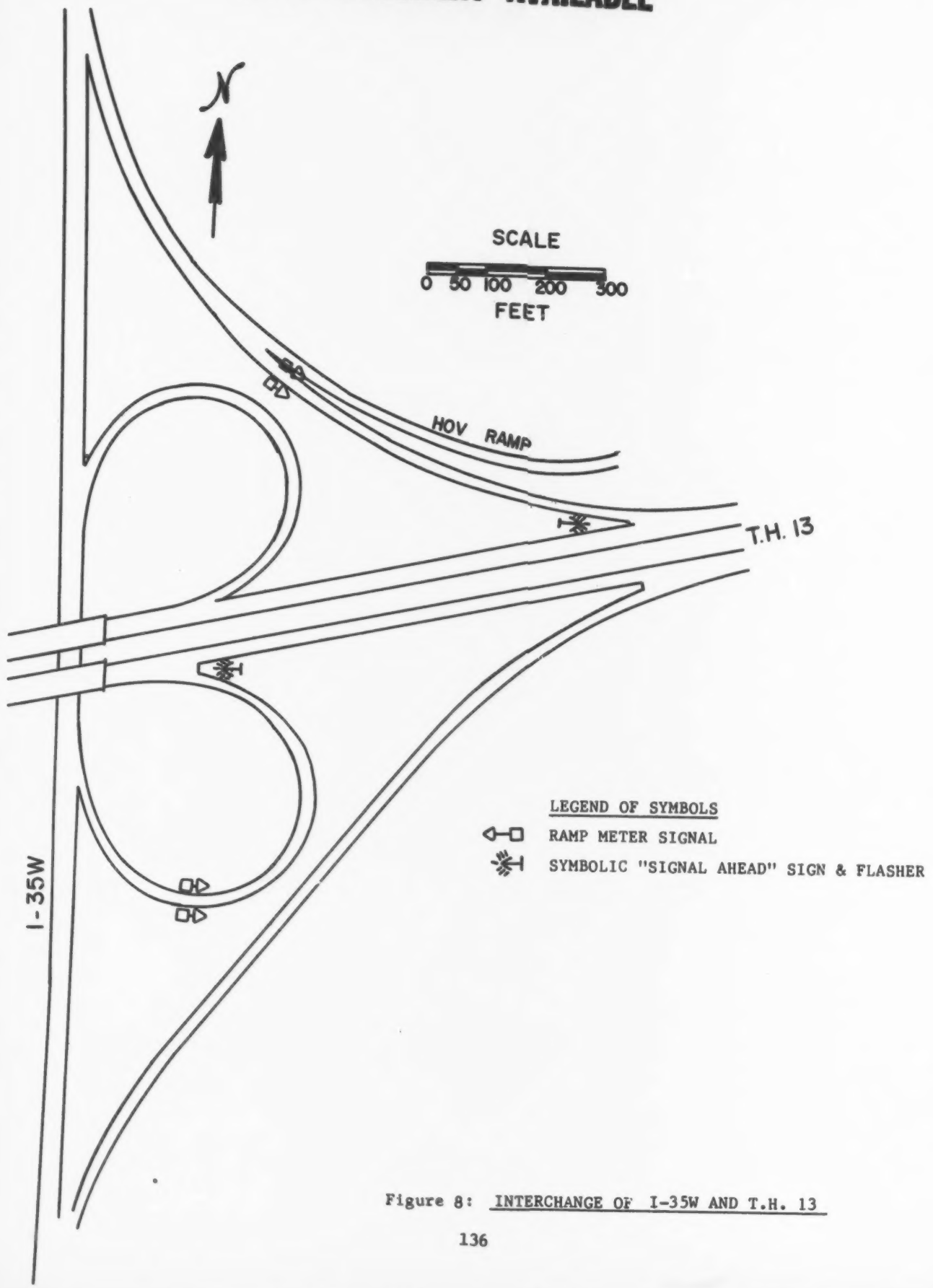

Figure 8: INTERCHANGE OF I-35W AND T.H. 13

low on this highway, and there has not been an accident problem. Despite the periodic extensive queuing and delay at this location, motorist compliance to the meters has been very good.

Ramp control at this interchange is absolutely essential to optimizing flow and minimizing accidents on the section of I-35W approaching the Minnesota River bridge, and has contributed very substantially to the benefits described earlier.

Note - for additional information on any of the Mn/DOT projects, please contact Mr. Glen Carlson at the following address: Mn/DOT Traffic Management Center, 1101 4th Ave. South, Minneapolis, Minnesota 55404 (phone no. 612-341-7500).

CONCLUSIONS

Determination of the need for freeway to freeway metering should be based on a system-wide analysis, taking into account the impact both downstream and at the interchange area. If freeway congestion is so severe that there is recurrent stopping of mainline traffic, control of freeway to freeway ramps with meters is a workable alternative. From a safety standpoint it seems more desirable to stop traffic under predictable, controlled conditions than to contend with uncontrolled, random conditions.

Freeway to freeway ramps are generally characterized by higher traffic volumes and operating speeds than local street entrance ramps, and special consideration must be given to the design of metering systems for them. Essential conditions for such installations include adequate storage, advance warning and sight distance. There is a special problem associated with the queue discharge capability at high volume ramps. Obviously, as the demand volume approaches or exceeds the maximum volume flow through the meter the ability to exercise an adequate range of control diminishes.

In some cases it becomes necessary to reconstruct freeway to freeway ramps to gain additional storage, increase discharge capacity, or to provide preferential treatment for HOVs. From a standpoint of geometrics, the loops of cloverleaf type interchanges seem to be the most difficult to meter due to the following problems:

- Queue storage space is limited.
- Excessive queuing may have an adverse impact on traffic operations in the acceleration-deceleration lane of the cloverleaf, and at certain locations may even disrupt traffic flow on the intersecting freeway.
- It is difficult, if not impossible, to reconstruct these ramps to provide additional starage or HOV bypass capability.

In those situations where concerns over storage, advance warning, and sight distance can be satisfied, freeway to freeway metering is a safe and effective traffic management strategy. Adverse public reaction to metering these connections appears not to be significantly different from metering surface street connections, and unusual problems associated with compliance and/or enforcement have not been noted.

*U.S. GOVERNMENT PRINTING OFFICE: 1982 522-046/8511 1-3

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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